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Développement méthodologique de l'Analyse du Cycle de Vie conséquentielle appliquée au secteur de la construction civile

Denise Tavares Lima de Almeida

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THÈSE

présentée par : **Denise TAVARES LIMA DE ALMEIDA**

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Methodological development of consequential life cycle assessment applied to the construction sector

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Abstract

The buildings and construction sector plays a key role in achieving sustainable development goals and is part of the strategic approaches to attain carbon neutrality in 2050. To achieve these ambitious commitments, the tools that are now applied in a unit of construction product, equipment, or building will need to be used in higher extensions (large-scale decisions). Considering the lack of a consensual framework for assessing the environmental consequences occurring in the construction sector, the main goal of this thesis was to propose a method to evaluate large-scale changes, such as the ones from public policies. Initially, a literature review was conducted aiming at identifying the strategies that are coupled with consequential life cycle assessment. The review showed that the most common is to use a computable equilibrium model for studying the economic interactions and monetary redistribution.

Transitioning to a more environmentally friendly economy introduces new dynamics in the whole economy, also affecting the financial system. Considering the misrepresentation of the latter in computable equilibrium models, this thesis proposes a method based on stock-flow consistent (SFC) models. These models explicitly take into account the monetary distribution with a rigorous accounting framework.

The main scientific contribution of the thesis was thus to propose a method that couples an SFC model with a dynamic input-output analysis (IOA) for obtaining the life cycle inventory. The flow changes are obtained by applying the IOA framework based on the environmentally extended multi-regional input-output table from Exiobase. The marginal stock changes are taken from the 'stocks database' developed in the thesis.

From a technical standpoint, the thesis applied the method to the French Recovery Plan, launched in 2020 to recover the French economy from Covid's pandemic crisis. Precisely, the thesis studied the budget dedicated to increasing the thermal retrofitting works substantially in France.

Greenhouse gas (GHG) emissions and two types of additional flows within the technosphere are assessed (amounts of waste generated and the energy consumption, embodied and direct consumption). The results show that the monetary redistribution induces consumption and the latter is significant, with a multiplier effect of around 18%. Compared with the life cycle environmental impacts of the equipment and insulating products, the induced consumption represents from 15% to 23% of life cycle greenhouse gas emissions, from 9% to 12% of life cycle energy use and from 11% to 13% of produced waste.

Considering that the main objective of conducting thermal retrofitting works is to reduce the energy consumption of buildings, the model considers that the energy savings take place

in a second period, where the environmental consequences are also assessed. The results show that the emissions occurring in France would be compensated within 1.2 years for the best scenario and 3.4 years for the worst scenario. However, when taking into account the global perspective, the GHG emissions would take from 2 to 8 years to be compensated. For waste, the results are less encouraging since the energy savings do not considerably reduce waste production. Therefore, the time needed to offset the extra production associated with thermal retrofitting fostered by the recovery plan is 12 years in the most optimistic scenario, only considering French activities, and 144 years in the less favorable scenario considering the global perspective.

The Ph.D. study concludes that the second-order effects, specifically income redistribution, are not negligible for public policies, especially when additional money is used through loans taken out to finance the policies. The consequential approach makes evident that imported GHG emissions, energy use and waste production are significant, highlighting the need to use holistic approaches to assess new policies' environmental impacts.

Résumé

Le secteur du bâtiment et de la construction joue un rôle clé dans l'accomplissement des objectifs de développement durable et fait partie des approches stratégiques visant à atteindre la neutralité carbone en 2050. Pour atteindre ces engagements ambitieux, les outils qui sont aujourd'hui appliqués dans une unité de produit de construction, d'équipement ou de bâtiment devront être utilisés dans des extensions plus importantes (décisions à grande échelle). Considérant l'absence d'un cadre consensuel pour évaluer les conséquences environnementales survenant dans le secteur de la construction, l'objectif principal de cette thèse était de proposer une méthode pour évaluer les changements à grande échelle, tels que ceux issus des politiques publiques. Dans un premier temps, une revue de la littérature a été réalisée dans le but d'identifier les stratégies couplées à l'analyse du cycle de vie conséquentielle. Cette revue a montré que la plus courante est l'utilisation d'un modèle d'équilibre calculable pour étudier les interactions économiques et la redistribution monétaire.

La transition vers une économie plus respectueuse de l'environnement introduit une nouvelle dynamique dans l'ensemble de l'économie, affectant également le système financier. Considérant la mauvaise représentation de ce dernier dans les modèles d'équilibre calculable, cette thèse propose une méthode basée sur les modèles stock-flux cohérents (SFC), vu qu'ils prennent explicitement en compte la distribution monétaire.

La contribution scientifique de la thèse est donc de proposer une méthode qui couple un modèle SFC avec l'analyse d'entrées-sorties (AES) pour obtenir l'inventaire du cycle de vie. Les changements dans les flux sont obtenus à partir des tableaux d'entrées-sorties multirégional à l'extension environnemental d'Exiobase. Les changements marginaux dans les stocks sont obtenus à partir de la 'base de données des stocks' développée dans la thèse.

D'un point de vue technique, la thèse a appliqué la méthode au Plan de relance français, lancé en 2020 pour redresser l'économie française après la crise pandémique de Covid, notamment ce qui concerne le budget dédié à l'augmentation substantielle des travaux de rénovation thermique en France.

Les émissions de gaz à effet de serre (GES) et deux types de flux supplémentaires au sein de la technosphère sont évalués : quantité de déchets générés et la consommation d'énergie (grise et directe). Les résultats montrent que la redistribution monétaire induit une consommation et que cette dernière est significative, avec un effet multiplicateur d'environ 118%. Par rapport aux impacts environnementaux du cycle de vie des équipements et des produits isolants, la consommation induite représente de 15% à 23% des émissions de GES, de 9% à 12% de la consommation d'énergie et de 11% à 13% des déchets produits.

Les économies d'énergie sont également évaluées. Les résultats montrent que les émissions survenant en France seraient compensées en 1,2 an pour le meilleur scénario et en 3,4 ans pour le pire scénario. Toutefois, si l'on prend en compte la perspective mondiale, le temps d'élève à de 2 ans à 8 ans. Pour les déchets, le temps nécessaire pour compenser la production supplémentaire associée aux travaux de rénovation est de 12 ans en ne considérant que les activités françaises, et de 144 ans en considérant la perspective globale.

L'étude de cette thèse conclut que les effets de second ordre, notamment la redistribution des revenus, ne sont pas négligeables pour les politiques publiques, en particulier lorsque des fonds supplémentaires sont utilisés par le biais d'emprunts contractés pour financer ces politiques. L'approche conséquentielle met en évidence que les émissions de GES importées, la consommation d'énergie et la production de déchets sont très importantes, ce qui souligne la nécessité d'utiliser des approches holistiques pour évaluer les impacts environnementaux des nouvelles politiques.

Un résumé étendu en français est disponible dans le Chapitre 7.

List of Abbreviations

Abbreviation	Definition
ABM	Agent-Based Modelling
AGEC	Anti-waste policy for a circular economy (in French *Anti-gaspillage pour une économie circulaire*)
ALCA	Attributional Life Cycle Assessment
BAU	Business-as-usual
BEUR	Billion euros
BIS	Bank for International Settlements
BLCA	Backcasting Life Cycle Assessment
BoP	Balance of Payments
BPM6	Balance of Payments and International Investment Position Manual
BREEAM	Building Research Establishment Environmental Assessment Method
BTC	By-product technology construct
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CBA	Consumption-based accounting
CDIS	Coordinated Direct Investment Survey
CDW	Construction and Demolition Waste
CGE	Computable General Equilibrium
CLCA	Consequential Life Cycle Assessment
CML	Institute of Environmental Sciences of Leiden University
CPE	Computable Partial Equilibrium
CPIS	Coordinated Potfolio Investment Survey
CRM	Critical Raw Material
CSTB	French Scientific and Technical Center for Buildings (in French *Centre Scientifique et Technique du Bâtiment*)
CTC	Commodity technology construct
DED	Default environmental data
DLCA	Decisional Life Cycle Assessment
DyLCA	Dynamic Life Cycle Assessment
EC	European Commission
EE-IOA	Environmentally extended input-output analysis
EE-IOT	Environmentally extended input-output table
EFI	European Forest Institute
EIA	Environmental impact assessment
ELCA	Ex-ante LCA
EPD	Environmental product declaration
ESA	European System of Accounts
ESG	Environmental, societal and governance
EU	European Union
FAOSTAT	Food and Agriculture Organization of the Statistics division of the United Nations
FAUST	Five Assets Unified Stock-flow Transactions
FC	Financial Corporations
FD	Final demand
GDDS	General Data Dissemination System
GDP	Gross domestic product
GG	General Government
GG-RP	General Government – Recovery Plan
GG-SA	General Government – Social Affairs

GHG	Greenhouse gas
GTAP	Global Trade Analysis Project
GTM	Global Trade Model
GWP	Global Warming Potential
HH	Households
HLCA	Hybrid Life Cycle Assessment
HS	High-skilled
HVAC	Heating, ventilation and air-conditioning
ICT	Information and communications technology
IIP	International Investment Position
ILCA	Integrated Life Cycle Assessment
ILCD	International Life Cycle Data System
ILO	International Labor Organization
ILUC	Indirect land-use change
IMF	International Monetary Fund
INSEE	French National Institute of Statistics and Economic Studies (in French *Institut National de la Statistique et des Etudes Economiques*)
IO	Input-Output
IOA	Input-Output Analysis
IOT	Input-Output Table
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JEDH	Joint External Debt Hub
JRC	Joint-Research Center
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
LIST	Luxembourg Institute of Science and Technology
LS	Low-skilled
ME&A	Middle East and Africa
MENFIS	*Modèle ENergie FIScalité des logements*
MEUR	Million euros
MFA	Mass Flow Analysis
MLCA	Macro Life Cycle Assessment
MPR	MaPrimeRénov'
MRIOT	Multi-Regional Input-Output Table
NACE	Statistical classifications of economic activities (in French *Nomenclature statistique des Activités économiques dans la Communauté Européenne*)
NDC	Nationally determined contributions
n.e.c.	Not elsewhere classified
NFC	Non-Financial Corporations
NLCA	Anticipatory Life Cycle Assessment
NLCS	National Low Carbon Strategy
NPISH	Non-Profit Institutions Serving Households
NZEB	Net zero energy building
OECD	Organization for Economic Cooperation and Development
PBA	Production-based accounting
PE	Partial Equilibrium
PLCA	Prospective Life Cycle Assessment
QEDS	Quarterly External Debt Statistics
R&D	Research and Development
RICS	Royal Institution of Chartered Surveyors
ROW	Rest of the World

SAM	Social Accounting Matrix
SBTi	Science-based target initiative
ScLCA	Scenario-based Life Cycle Assessment
SDDS	Special Data Dissemination Standard
SDG	Sustainable Development Goals
SNA	System of National Accounts
SUT	Supply and Use Table
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental impacts
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environmental Programme
WGBC	World Green Building Council

List of countries and regions

Abbreviation	Definition	Abbreviation	Definition
AT	Austria	KR	South Korea
AU	Australia	LT	Lithuania
BE	Belgium	LU	Luxembourg
BG	Bulgaria	LV	Latvia
BR	Brazil	MT	Malta
CA	Canada	MX	Mexico
CH	Switzerland	NL	Netherlands
CN	China	NO	Norway
CY	Cyprus	PL	Poland
CZ	Czech Republic	PT	Portugal
DE	Germany	RO	Romania
DK	Denmark	ROW	Rest of the World
EE	Estonia	RU	Russia
ES	Spain	SE	Sweden
FI	Finland	SI	Slovenia
FR	France	SK	Slovakia
GB	United Kingdom	TR	Turkey
GR	Greece	TW	Taiwan
HR	Croatia	US	United States
HU	Hungary	WA	ROW Asia and Pacific
ID	Indonesia	WE	ROW Europe
IE	Ireland	WF	ROW Africa
IN	India	WL	ROW America
IT	Italy	WM	ROW Middle East
JP	Japan	ZA	South Africa

Liste d’abréviations

Liste d’abréviations utilisées dans la version française

Terme	Définition
ACV	Analyse du cycle de vie
ACV-A	Analyse du cycle de vie attributionnelle
ACV-C	Analyse du cycle de vie conséquentielle
ADEME	Agence De l'Environnement et de la Maîtrise de l'Énergie.
AES	Analyse d’entrées-sorties
AFM	Analyse des flux de matériaux
AMORCE	Association de l’observatoire des réseaux de chaleur et de froid
BAU	*Business-as-usual*
CBC	Comptabilité basée sur la consommation
CBP	Comptabilité basée sur la production
CSTB	Centre Scientifique et Technique du Bâtiment
DEP	Déclarations environnementales de produits
EIE	Evaluation des incidences sur l'environnement
FMI	Fond Monétaire International
GES	Gaz à effet de serre
ISBLSM	Institutions sans but lucratif au service des ménages
MCS	Matrice de comptabilité sociale
MEG	Modèle d’ équilibre général
MENFIS	Modèle ENergie FIScalité des logements
MEP	Modèle d’équilibre partiel
MFT	Matrice des Flux de Transactions
MPR	MaPrimeRénov'
MS	Ménages
MS-FQ	Ménages faiblement qualifiés
MS-HQ	Ménages hautement qualifiés
MS-MQ	Ménages moyennement qualifiés
ODD	Objectifs de développement durable
OIT	Organisation Internationale du Travail
PIB	Produit intérieur brut
PNUE	Programme des Nations Unies pour l’Environnement
PRG	Potentiel de réchauffement global
ROW	Reste du Monde
SCN	Système de comptabilité nationale
SEC	Système européen des comptes
SF	Sociétés financières
SNBC	Stratégie Nationale Bas Carbone
SNF	Sociétés non financières
TES	Tableaux d’entrées-sorties
TES-EE	Tableaux d’entrées-sorties à extensions environnementales
TMES-EE	Tableaux multirégionaux d'entrées-sorties à extensions environnementales

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List of symbols

I - Transaction-flow matrix symbols

Symbol	Description	Code in the System of National Accounts
$C^{R,U}{}_k$	Final consumption expenditure	P3
$GCF^{R,U}{}_k$	Gross capital formation	P5G
$Ex^{R,U}{}_k$	Exports	P6
$Im^{R,U}{}_k$	Imports	P7
$OS^{R,U}{}_k$	Operating surplus	B2G
$W^{R,U}{}_k$	Wages and salaries	D11
$ESC^{R,U}{}_k$	Employer's social contributions	D12
$TxP^{R,U}{}_k$	Taxes on products	D21
$OTx^{R,U}{}_k$	Other taxes on production	D29
$IL^{R,U}{}_k$	Interests on loans	D41
$ID^{R,U}{}_k$	Interests on deposits	D41
$TI^{R,U}{}_k$	Taxes on income	D5
$SC^{R,U}{}_k$	Social contributions (employee)	D61
$SB^{R,U}{}_k$	Social benefits	D62
$CT^{R,U}{}_k$	Other current transfers	D7
$Dp^{R,U}{}_k$	Deposits	F2
$Db^{R,U}{}_k$	Debts	F3,F4,F5

R=resource, U= use; k= institutional sector (NFC, HH, GG, FC, ROW)

II - Distribution model symbols

Symbol	Description
Z	Inter-industry intermediate inputs matrix
A	Technical coefficients matrix
B	Initial value-added matrix
$\tilde{B}$	Coefficient matrix of value-added
C	Final consumption matrix
$\tilde{C}$	Marginal consumption matrix
D	Changes in environmental stressors matrix (life cycle inventory)
E	Environmental extension matrix (with the environmental stressors)
$\tilde{E}$	Environmental coefficients matrix
F	Final demand matrix
G	Changes in value-added matrix
H	Expenditure on induced consumption matrix
L	Leontief's inverse
x	Total outputs vector

III - Greek symbols

Symbol	Description
α_i	Propensity to consume out of extra income of income group 'i'
μ	Share of 'direct investment' attributed to financial corporations
φ	Share of 'other investments' attributed to financial corporations
θ	Rate for the taxes on income
ρ	Rate for social contributions
γ_k	Gross value-added share of institutional sector 'k'

k= institutional sector (NFC, HH, GG, FC, ROW), i= income group (low-skilled, medium-skilled, high-skilled households)

Glossary

The main terms used in the thesis are defined in this glossary. The goal here is to provide the terminology considered in this research and not to be exhaustive in terms of definitions that are important in the context of studies in construction sector and environmental assessments.

Term	Definition
Agent-based model	Dynamic socio-economic models that take into account the interaction between the different agents involved in the study. Agents are completely autonomous and make decisions according to a set of rules in common to all entities that are regrouped as the same agent (Bonabeau, 2002; Davis et al., 2009; Querini and Benetto, 2014).
Direct effects	Direct effects are those pertaining to the sector that is directly affected by the shock (Breisinger et al., 2009). For example, an exogenous increase in demand for window exports has a direct impact on the glass sector.
Economic activity	An economic activity is a process that, based on its inputs, leads to the manufacture of a good or the provision of a service (INSEE, 2021a).
Economic model	A generic term to define a mathematical framework that intends to hypothetically describe the real economic interactions by using a set of mathematical variables and equations (Mankiw, 2009).
Economic sector	A group of economic activities aggregated by nature of activity (Agriculture, Industry, Construction, Trade, etc.) (INSEE, 2021a).
Environmental Impact Assessment	A study conducted to identify, describe and assess the likely environmental impacts of a proposed project. It must include the direct and indirect effects on human beings, fauna and flora, soil, water, climate, landscape, material assets, cultural heritage, and inter-relations between them (EU Directive 2011/92/EU).
First-order effects	Activities that occur as a result of a specific expenditure (consumption decision) until it has overflowed from these activities in the form of payments for primary factors (wages, production taxes, entrepreneurial income, and rents).
General equilibrium model	A system of equations that are solved simultaneously to find an economy-wide equilibrium. The system of equations describes the motivations and behavior of all producers and consumers in an economy and the linkages between them. For achieving the equilibrium, the quantities of supply and demand are equal in every market (Burfisher, 2012).
Indirect effects	Effects from the main sector's linkages to other sectors and parts of the economy. These indirect linkages can, in turn, be separated into production and consumption linkages (Breisinger et al., 2009).

Institutional sector	A sector that includes the institutional units with similar economic forms of behaviour characterised by their main function and the nature of their activity (INSEE, 2021a).
Institutional unit	A basic economic decision-making centre characterised by the uniqueness of its behaviour and its decision-making autonomy in the fulfilment of its main function (INSEE, 2021a).
Life Cycle Assessment	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040:2006).
Marginal suppliers	The suppliers that will actually respond to the marginal change in demand (UNEP, 2011).
Material Flow Analysis	An evaluation method which assesses the efficiency of use of materials using information from material-flow accounting (EEA, 2020).
Partial equilibrium model	A system of equations that are solved simultaneously to find an equilibrium in one part of the economy. The theory is based on the ceteris paribus assumptions, i.e., the income and prices in the rest of the economy stay fixed (Burfisher, 2012).
Rebound effects	Derived changes in the overall production or consumption caused by (un)expected responses from systemic factors, such as money, time, technology, and space (Font Vivanco and van der Voet, 2014).
Second-order effects	Effects occurring after the original expenditure has been received by the primary factor agents (laborers, government or recipients of tax redistributions, entrepreneurs, or rentiers), i.e., as a result of re-spending the original amount in subsequent spending loops.
Stock-flow consistent model	A macroeconomic model with heterogeneous, interacting agents of the real economy and finance. The system of equations describes the behavioral rules (e.g. regarding investment and consumption decisions), following four principles: flow consistency, stock consistency, stock-flow consistency and quadruple entry (Zezza and Zezza, 2019).
Thermal retrofitting work	A retrofit work carried out in a building to improve its thermal performance. It may consist of one or more modifications (replacement, installation of new equipment, etc.) to reduce energy requirements for heating or cooling the building.

First part

Introduction

The buildings and construction sector, through companies, institutions and associations, has engaged in specific initiatives and signed agreements worldwide to reduce buildings emissions, waste, and energy consumption. Besides, the sector is a key actor for countries to achieve carbon neutrality in 2050. Therefore, there is a perception that stakeholders (clients, customers, investors, government, etc.) are increasingly demanding concrete actions so that the engagements and agreements will have an actual effect, particularly with respect to the sustainable development goals. One of the consequences of this is that the measures that are now being applied in one unit of construction product, equipment, building, or even in neighborhoods, will need to be expanded to higher dimensions (large-scale decisions).

The French Scientific and Technical Center for Buildings (CSTB, for French *Centre Scientifique et Technique du Bâtiment*) has an active role in developing tools for including the environmental and energy performances in mandatory requirements for constructing new buildings in France. Yet, the tools currently used by the sector to evaluate the potential environmental benefits and burdens of the proposed actions are mainly applied in small-scale decisions (units of construction product, units of equipment, and units of buildings).

Accordingly, the question that appears evident is "are these benefits in smaller-scale decisions still beneficial to the environment when they are propagated in larger extensions, where indirect effects could be significant?". And also, "whether and to what extent do these actions contribute to the sustainable development goals?".

The hypothesis of the thesis is that the consequential approach is more appropriate for helping answer these questions since the upscaling from low to higher applications may present cause-effect relationships that go beyond the product supply chain, and still, beyond the normative system boundaries.

For this purpose, the main objective of this thesis is to propose a methodological framework for carrying out a consequential LCA (CLCA) applied to large-scale decisions in the construction sector.

The results are as follows:

- The development of a CLCA methodology applied to the construction sector, including second-order effects
- A practical case study of the application of the consequential LCA methodology developed with the results of environmental simulations

The works of the thesis are organized into three parts, composed of six chapters, as presented in Figure I - 1. The first part concerns the scientific and technical background, and also provides the scientific proposition for answering the research questions. The second part focuses on the application, testing the theories and presenting some possible results that can be obtained from the proposed method. Finally, the third part concludes the research work, with final feedback on the main research question.

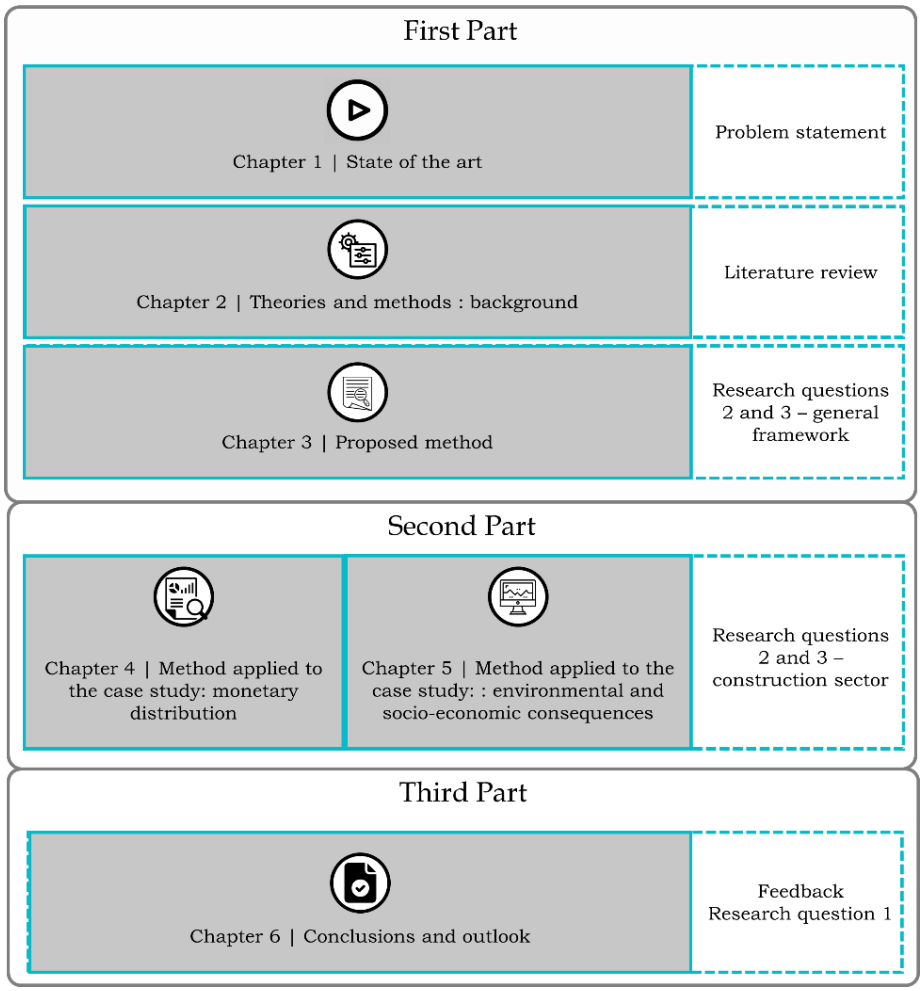

Figure I - 1 | Outline of the thesis

Chapter 1 is dedicated to contextualizing the research conducted in this thesis in global and French contexts. It also presents the state of the art of consequential approach and provides the reader with a literature review on the use of CLCA in the construction sector, concluding with the problem statement while introducing the scientific research questions. **Chapter 2** provides a wider dimension of CLCA studies and shows how socio-economic models can help these assessments. Firstly, a literature review on the use of these models in CLCA is presented, needing to explore sectors that have a similar problematic relative to the consequential effects. In a second moment, the review is focused on the models previously identified, providing their definitions, advantages and limitations for the purpose of the thesis.

Chapter 3 is focused on the main contributions of the thesis, which is the methodological framework. The methodology proposed in this thesis is based on the conventional LCA framework defined by the international standards ISO 14040-44 (2006), keeping the four phases of conventional LCA as defined by ISO14040-44. The second phase of this general framework analyzes the life cycle inventory. This phase is the most challenging from the consequential point of view because the 'indirect effects' must be included here. Thus, in this phase, an input-output (IO) stock-flow consistent (SFC) model is integrated through a step-wise method developed in this thesis, as presented below:

- Step 1: Defining the exogenous perturbation
- Step 2: Determining the transactions that are included in the model
- Step 3: Calculating the monetary distribution
- Step 4: Accounting the changes in flows in a Transaction-Flow Matrix (TFM)
- Step 5: Calculating the income re-distribution

The first step consists in defining the **exogenous perturbation** accordingly to the goals of the study. The perturbation must represent the functional unit of the study. The second step is determining the transactions that will be part of the study and selecting the pertinent institutional sectors for the study. The third step integrates a **monetary (re)distribution model based on input-output (IO) analysis**. Finally, the fourth step consists of accounting for the changes in the transaction flows in a **transaction-flow matrix** (TFM) and analyzing the stock changes that will affect another round of distribution, going back to step 2. The link between steps 4 and 3 can be considered as a fifth step. At the end of each round, the changes in substance emissions and natural resource consumption are calculated using the hybrid IO-LCA framework.

The methodology developed in the thesis is coupled with an environmentally extended multi-regional input-output (EE MRIO) table, namely EXIOBASE, version 3, which covers 44 countries, 5 rest of the world regions, 163 industries, 200 products, 3 employment skill levels per gender, 417 emission categories and 662 materials and resources categories.

Chapter 4 applies the methodology detailed in the previous chapter to a case study, which is the part of the French Recovery Plan focused on fostering thermal retrofitting works. The Recovery Plan was launched in 2020 by the French Government with a budget of €100 billion to support economic activity and job creation. The particular budget of 5.2 billion euros dedicated to increasing the energy efficiency of the built stock represents the case study of this thesis. The initial perturbation is an increase in demand for thermal retrofitting works, resulting in energy savings. The latter are thus a decrease in demand for energy products, which is the second period perturbation. For quantifying these exogenous perturbations, three approaches were developed: a simplified version of the total budget, and a detailed and a simplified version of the budget dedicated to residential buildings.

In the first one, the "construction works" EXIOBASE activity responds to the increase in demand for thermal retrofitting works. In this simple version, all the budget for retrofitting

residential and public buildings is considered (€5.2 billion). In both versions of studying "only residential buildings", households conduct thermal retrofitting works in their houses and apartments by using the money from financial aid (€2.0 billion) and their stocks (€3.8 billion). In the detailed version, a prospective econometric model was used to quantify the typology of the retrofitting works, characterizing the marginal activities that are affected by an increase in financial aid thanks to the recovery plan. In the simplified version, the same assumptions as those of "total budget" were applied. This chapter highlights all assumptions and particularities of the proposed methodology to the French case study.

Chapter 5 presents the greenhouse gas emissions, waste production and energy consumption obtained by applying the proposed method in the case study. The chapter also discusses socio-economic impacts, namely the changes in net worth, the marginal utility, balance of trade and the relationship between loans and balance of trade for the selected countries. Finally, **Chapter 6** provides the conclusions, highlighting the limitations and proposing some opportunities for further work in both scientific and technical sides.

The articles written during this thesis are listed in Appendix 1.

1

State of the art

1.1 Construction sector, a key actor in achieving sustainable development goals

Buildings and construction activities represent the largest share of energy consumption, greenhouse gas (GHG) emissions, and wastes production in a global perspective, being responsible for 36% of total final energy consumption, 37% of total CO2 emissions in 2020 (UNEP, 2021) and 36% of total wastes in 2015 (UNEP and ISWA, 2015). Regarding their contribution to resource depletion, from 30% to 50% of total material use in Europe goes to constructing buildings, namely iron, aluminium, copper, clay, sand, gravel, limestone, wood and building stone (Ecorys, 2014). The buildings and construction sector consume around 65% of total aggregates (sand, gravel and crushed rock) and 20% of total metals (Ecorys, 2014). The sector's demand for fifteen out of the thirty critical raw materials (CRM) defined in 2020 by the Joint-Research Center of the European Commission (EC-JRC, 2020) is substantial. Some examples of CRM that are highly consumed by the sector are niobium (51% of European finished products goes to construction elements, e.g. heavy infrastructure needing high quality of steel), magnesium (34% of European finished products goes to the construction systems, such as cement), and borate (59% of finished products consumed in Europe goes to glass products).

From the economic standpoint, the sector's contribution to total gross domestic product (GDP) varies from country to country, for example, among the fifty-six United Nations Economic Commission for Europe (UNECE) member countries, it ranges from 1.4% in Greece to 10.8% in Kyrgyzstan (UNECE, 2021), as can be observed in Figure 1.1.

It is estimated that the construction sector provides 7% of total global employment, corresponding to 220 million workers worldwide (ILO, 2019). The construction sector's activities are linked to many other sectors, such as raw material suppliers (e.g. metal, non-

metal industries, energy sector), materials transportation, waste treatments, and these indirect employments are estimated to be substantially higher than the direct employments in construction activities (ILO, 2019).

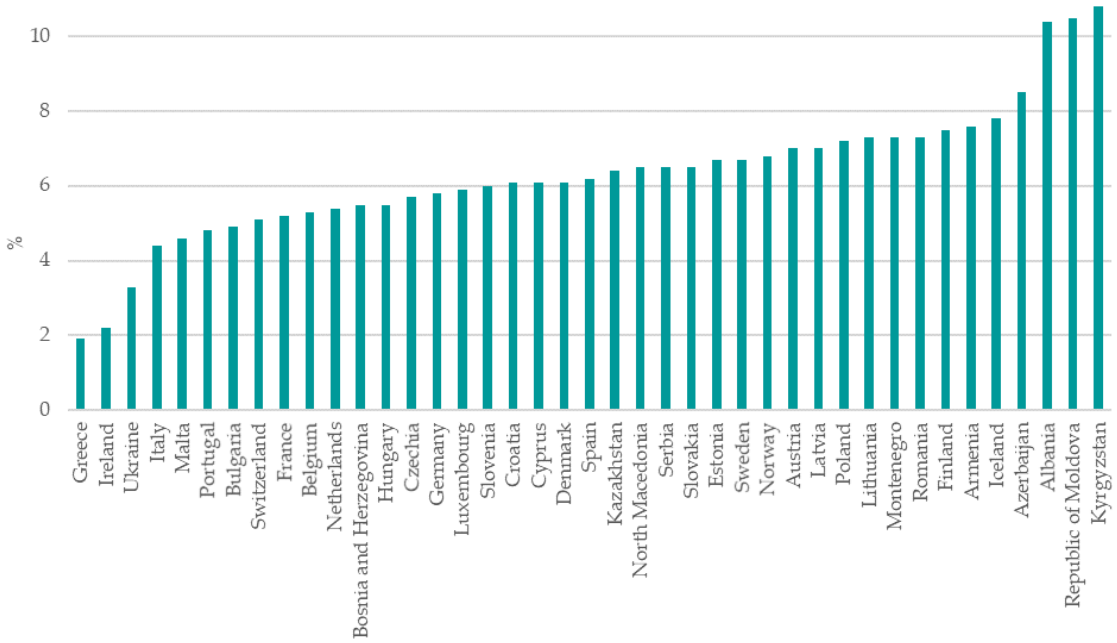

Figure 1.1 | Share of construction sector in European countries' national GDP in 2020 (UNECE, 2021)

The surveys conducted by the Royal Institution of Chartered Surveyors[1] (RICS, 2021), under the World Built Environmental Forum 2021, showed that the main concerns of worldwide professionals of the sector with respect to sustainability factors are: minimizing waste, reducing operational carbon emissions, improving the resilience of products, materials, and components (see Figure 1.2). The relative importance of these above-mentioned issues varies across the regions, for example, in the Middle East and Africa (ME&A), minimizing water consumption appears with a high-level of importance (mentioned by more than half of the respondents) while this factor is only mentioned by around 30% of respondents in Europe. On the other hand, a reduction in the embodied carbon emissions appears with high importance for European respondents while less than 25% of ME&A's respondents mention this factor as important.

[1] The Royal Institution of Chartered Surveyors (RICS) is a global professional body for surveyors, founded in London, in 1868. The goal of RICS is to establish and enforce standards in the development and management of land, real estate, construction and infrastructure. Under the World Built Environment Forum, RICS conducts a set of surveys with thousands of professionals from the worlds of commercial real estate and construction, including 30 countries. More information is available at: https://www.rics.org/uk/

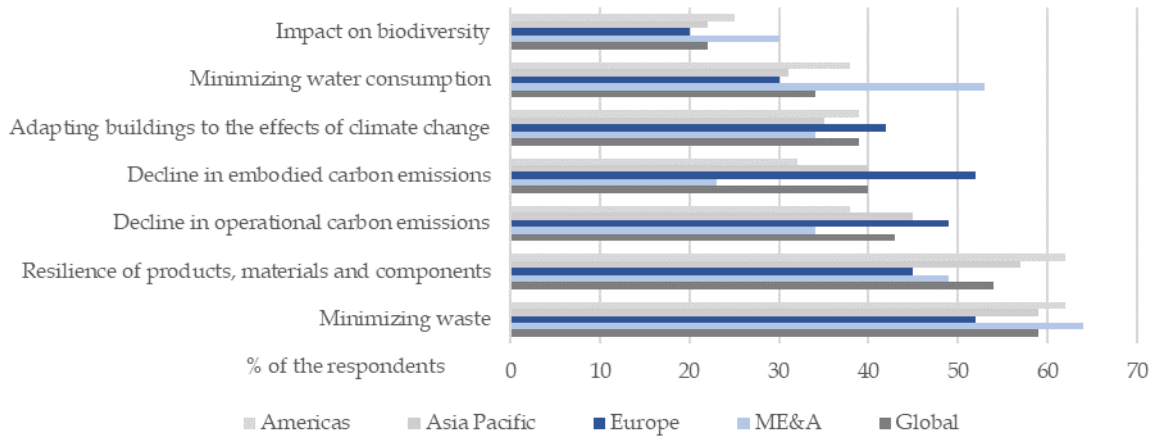

Figure 1.2 | Importance of sustainability issues in construction projects according to construction sector respondents (Adapted from (RICS, 2021))

As presented in Figure 1.3, also according to the RICS's surveys conducted in 2021, when construction sector professionals were questioned if they measure the embodied carbon emissions of their projects, 72% of the respondents answered that they did not measure any embodied carbon of their projects. Among them, around 18% of respondents mentioned that they would measure carbon emissions if there was a standardized approach. For those performing some sort of measurement, 14% of the respondents answered that this affects their choice of materials and components and the other 14% answered that this does not have any effect on their choices for construction products.

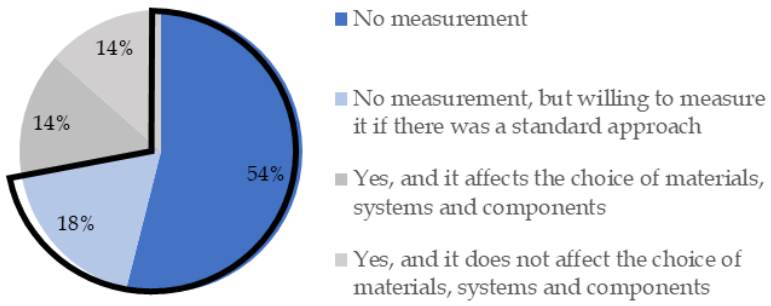

Figure 1.3 | Percentages of construction sector respondents to the measurement of construction projects' embodied emissions, global level (Adapted from (RICS, 2021))

These results differ at regional levels due to varying practices in construction among global regions. In Europe, for example, the number of respondents not measuring embodied carbon emissions drops to 45%, and the influence of measuring them in the decision for less emitting options rises to around 20%. Moreover, around 19% of European respondents

(following the same proportion as it is at global perspective) mentioned that they are willing to measure embodied carbon emissions of construction projects if there is a standardized approach (RICS, 2021), even if in the European Union there exists a common Standard for this purpose, namely the European Standard EN 15804. The reason for this is the lack of knowledge of the existing standard, which can be associated with there being no obligation to apply it in most countries.

These numbers show that the buildings and construction sector, in general, is willing to reduce its impacts, at different levels across the world, and to invest in environmental, societal and governance (ESG) good practices. Some of the reasons for this are demand from clients, stakeholders and customers, increased awareness of ESG risks and opportunities, brand image and reputation, regulatory requirements, a rise in ESG available data, research and analytics and higher potential financial returns (RICS, 2021).

The demand from stakeholders is the driving factor the most frequently mentioned by the sector professionals, at a global level. In Europe, for more than 70% of respondents, the demand of residents for green/sustainalble buildings has risen modestly (55%) or significantly (15%) in the 12 months preceding the survey. Concerning investors, the perception of respondents in Europe is even more pronounced, for more than 30% it rose significantly and for 45% it rose modestly in the 12 months preceding the survey, as presented in Figure 1.4.

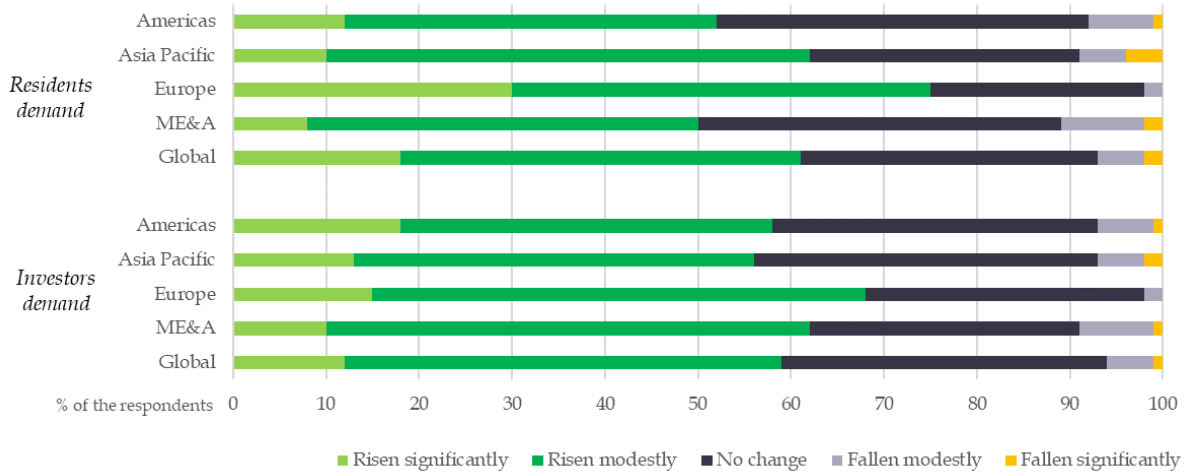

Figure 1.4 | Perception on the change in residents and investors demand for green/sustainable buildings in the 12 months preceding the survey (Source: (RICS, 2021))

The increase in demand from residents and investors for sustainable buildings and the aforementioned factors driving the investment in ESG activities are examples of pressures that different actors put on the buildings and construction sector for more sustainable practices. This pressure has led the sector to commit to the transition to **net zero emissions by 2050**. Some examples of initiatives that the sector (through companies, agencies, etc.) has committed to are Race to Zero campaign, Zero Carbon Buildings for All and the Science-based target initiative (UNEP, 2021).

The first one is a global initiative for encouraging leadership towards sustainable growth, which was signed by 66 companies from the construction sector (UNFCCC, 2022). Zero Carbon Buildings for All is a coalition to decarbonize the building sector, launched by United Nations in 2019, following the Net Zero Emissions Buildings Commitment set by the World Green Building Council (WGBC). This commitment involves the whole life cycle GHG emissions of buildings and applies to new buildings and also the retrofit of the existing ones. More than a hundred companies, around thirty cities and 6 regions have signed this commitment (WGBC, 2022). Science-based target initiative (SBTi) is a partnership between Carbon Disclosure Project, United Nations Global Compact, World Resources Institute and World Wide Fund for Nature to mobilize the private sector to act and lead on climate action, showing the companies how much and how quickly they need to reduce their GHG emissions (SBTI, 2022). More than 200 companies in the construction sector have committed to the SBTi, being one of the largest sectors joining the initiative (UNEP, 2021).

At a country-level, the policies mentioned in the nationally determined contributions (NDC) to achieve the Paris Agreement, updated in 2021 by the signatories, include the shift to low or zero-carbon fuels in buildings for 28% of the parties and energy-efficiency improvement in buildings for 63% of the parties. The latter is the second most referred to mitigation option among all, following the renewable energy generation, which was cited by 84% of the parties (UNEP, 2021).

Recently in Europe, some countries have launched new policies to reduce the whole life cycle GHG emissions of new buildings. Denmark, the Netherlands and France have approved regulations for constructing new buildings based on the whole-life cycle GHG emissions. In Denmark, the Danish building code has introduced a threshold for all new buildings with a surface greater than 1,000 m², being effective by 2023. The initial threshold limit value will be reduced progressively with a target of 5 kg CO_2eq/m²/year set to 2030 (Ministry of the Interior and Housing, 2021). In the Netherlands, the Building Environmental Performance (from Dutch *MilieuPrestatie Gebouwen (MPG)*) is needed for providing environmental allowances to new residential and tertiary buildings having a floor area larger than 100 m², effective since 2018. The methodology applied to obtain the MPG of a building was developed at a national level and is based on the principles of Life Cycle Assessment (LCA) (Netherlands Government, 2018). France's new regulation is detailed later in this chapter.

The United Kingdom (UK), Germany and Switzerland have LCA requirements for constructing public buildings. In the UK, the Government announced in 2020 a requirement for whole life cycle GHG assessments for all public works projects and programs (UK Government, 2020). In Germany, the Assessment System for Sustainable Building (in German *Bewertungsystem Nachhaltiges Bauen (BNB)*) is a tool for planning and evaluating public construction projects, based on LCA methodology (Germany Government, 2020). The tool is

linked to the German sustainability information database platform called Ökobaudat[2], which contains more than 1,400 environmental product declarations (EPD) of construction products and equipment. In Switzerland, the label Minergie, created in 2001 for providing energy performance certifications, has included the GHG emissions from life cycle perspective since 2016 (Minergie-ECO) and a minimum level is mandatory for granting allowances for constructing new public buildings (Minergie, 2018). The Swiss Sustainable Building Standard (SNBS) covers other sustainability aspects than Minergie-ECO, for example, level of comfort, contribution to regional/local economy; and was updated in 2021 to be combined with the latter (Minergie, 2021).

Finland, Sweden, and Belgium have developed EPD databases for life cycle GHG emissions of construction products, and both Scandinavian countries are also planning to implement new regulations for 2025 and 2027, respectively (Toth et al., 2021). According to UNEP (2021), European Union will probably have a common regulation in near future for requiring the measurement of the whole-life cycle GHG emissions of new buildings and imposing thresholds.

Moreover, in a long-term perspective, the European Union aims to be neutral in carbon emissions by 2050. Each member state has developed a mid- and long-term net-zero GHG emissions national strategies for achieving neutrality in 2050, of which buildings and construction sector plays an important role.

From a broader perspective, in 2015 the United Nations member states adopted the Sustainable Development Goals (SDG) as a call for action. The list of the 17 SDGs and their objectives is presented in Figure 1.5. These 17 goals are defined in a list of 169 targets, which are measured and tracked by 231 indicators (UNEP, 2015).

Some of the SDGs can be easily associated with the construction sector, such as clean water and sanitation (SDG6), affordable and clean energy (SDG7), industry, innovation and infrastructure (SDG9), and sustainable cities and community (SDG11). However, the sector can contribute to all of the SDGs, directly or indirectly, through its activities, the effects of its activities on the society and the governance of the sector's companies. For example, buildings that are designed (or redesigned) to improve biodiversity, save water, resources and help to protect the forests, thus contributing to the SDG 15, specifically the targets 15.2, 15.5 and 15.9.

The target 15.2 is to promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally, so that implementing nature and vegetation in cities would help to achieve this target. The target 15.5 is take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species. The actions on providing green urban spaces and more

[2] Available at https://www.oekobaudat.de/en.html

importantly not building over natural habitats important for preserving biodiversity are crucial to help achieving this target. Finally, the target 15.9 is to integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts, which can be achieved through the integration of biodiversity in the core of urban plans.

Figure 1.5 | All 17 SDGs (UNEP, 2015)

A focus on France

The developed methodology of this thesis is applied in a case study in France, which is in a particularly advanced position regarding regulatory whole-life cycle GHG emissions requirements for constructing new buildings (new regulation RE 2020 detailed later in this chapter). In France, the residential and tertiary sector emitted 75.1 $MtCO_2e$ in 2019, representing around 17% of total national emissions, and the total manufacturing industry (including construction) represented around 18% of total emissions (Citepa, 2021). Concerning consumption of final energy, residential and tertiary sectors represented around 46%, and industries (including the construction industry) represented 19%. It is estimated that the

buildings and construction sector produces 42 million tons of waste by year, causing significant costs for cleaning them of around 340 to 420 million euros (MTE, 2021a). Besides, the sector's activities represented 5.6% of total GDP, 5.5% of total employees (INSEE, 2021b).

Some actions have been implemented to reduce these numbers. The National Low Carbon Strategy (NLCS) (MTES, 2020) from 2020, for example, defined GHG emission targets for France as roadmap for climate change mitigation, declining the national goals into sector targets. The two main objectives of the NLCS are to achieve carbon neutrality in 2050 on the national territory (emissions occurring in France) and to reduce the carbon footprint of French people, including services and consumption goods coming from outside the French territory. These objectives imply the need for holistic and interdisciplinary actions, covering all economic activities.

Figure 1.6 presents the intermediate targets, called carbon budgets, at a national level. The first carbon budget was a very short-term target for the period of 2015-2018, which projected a decrease in 2.2% per year and in reality, the decrease was 1% per year in average. The second carbon budget foresees average emissions of 422 $MtCO_2eq$ for the period of 2019-2023, in total, while 383 $MtCO_2eq$ including the land sector. The third carbon budget is 359 $MtCO_2eq$ for the period of 2024 to 2028, 2 $MtCO_2eq$ lower when considering the land sector, and 300 $MtCO_2eq$ for the period of 2029 to 2033. The carbon sinks represented in green are projected to be 39, 38 and 42 $MtCO_2eq$ in the second, third and fourth carbon budgets, respectively.

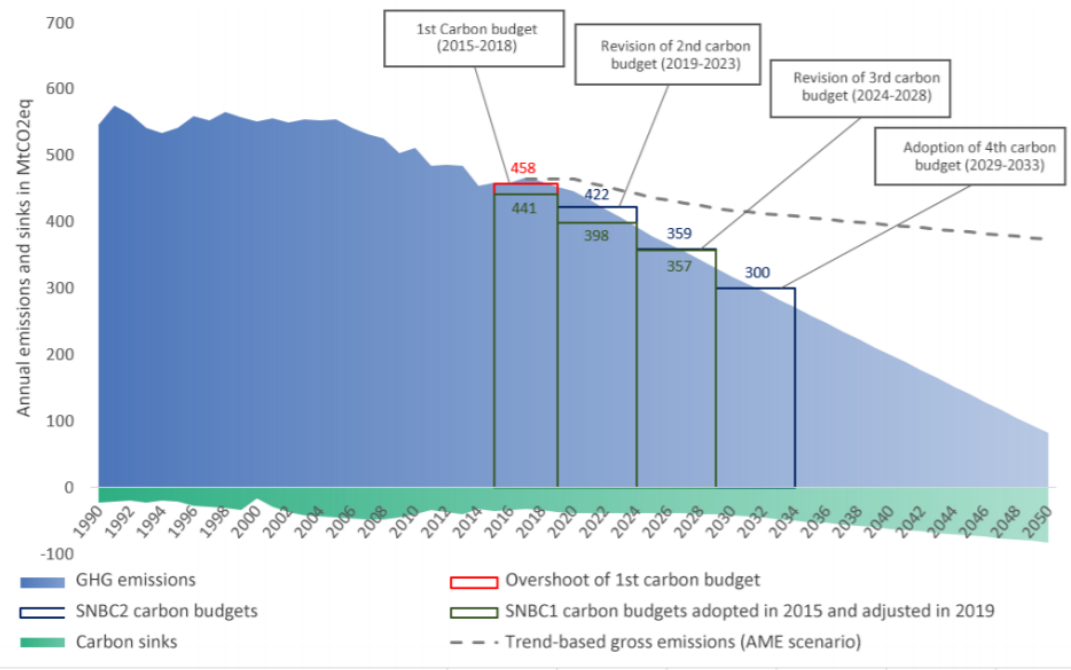

Figure 1.6 | Historical and projected GHG emissions, national level (from (MTES, 2020))

The NLCS sets two targets specific to the construction sector (highlighted in red in Figure 1.7). The first one is a reduction of 49% of GHG emissions by 2030, when compared to 2015 emissions and the second is to achieve neutrality in 2050. The annual reduction rates to achieve these targets are reductions of 2.87 $MtCO_2eq$ by year from 2015 to 2030 and 2 $MtCO_2eq$ by year from 2030 to 2050.

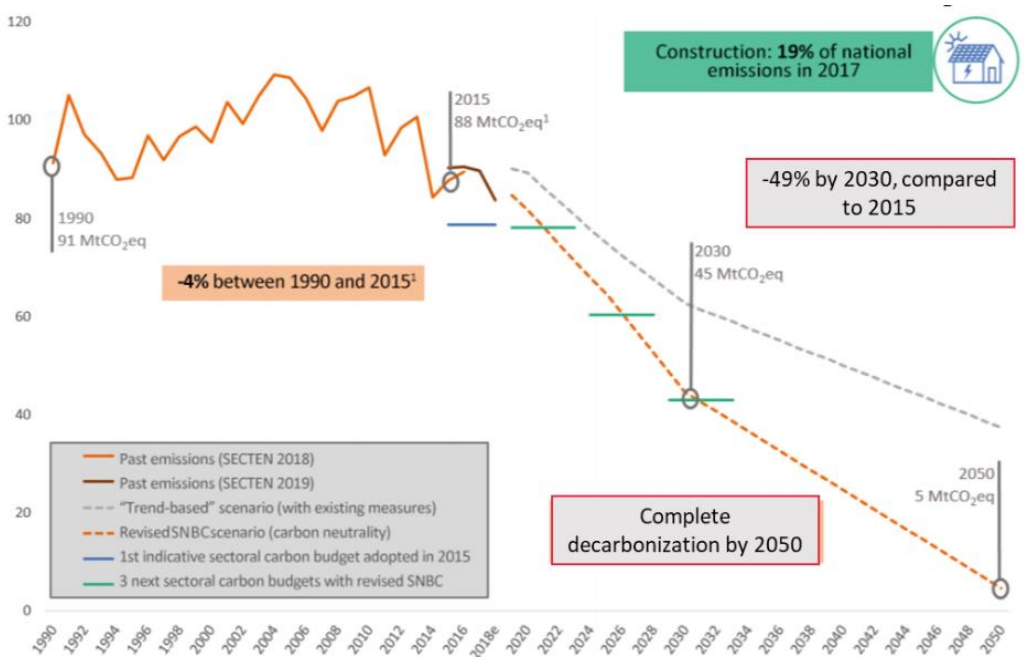

Figure 1.7 | Historical and projected GHG emissions of buildings ($MtCO_2eq$) (from MTES, 2020)

For achieving these targets, the Government has built four strategic measures: to guide a change in the energy mix (towards net zero carbon emissions), to encourage the thermal renovation so that all residential and tertiary buildings will be considered as low consumption buildings, to improve the energy and carbon performance levels of new buildings, and to aim for more energy-efficient equipment and moderate use.

The first measure applies to both new and existing buildings. The idea is to complement the already existing energy efficiency criterion with GHG emissions thresholds in the existing public policy instruments. The second measure concerns the massive adoption of thermal renovation in existing buildings through fiscal incentives, efforts in research, innovation and development to improve the knowledge of the built stock and other specific actions to tertiary buildings.

The third strategic measure for achieving the proposed targets focuses on new buildings. The NLCS mentions the importance of accounting for life cycle GHG emissions and adopting emissions thresholds for construction allowances in future regulations. In this sense, since 2004, France has established an EPD database called INIES[3] to gather the EPDs of construction

[3] INIES: French EPD database available at: www.inies.fr

products and equipment that are distributed in the country. There is also an EPD database for equipment called PEP Ecopassport, which is focused on electrical, electronic and HVAC (heating, ventilation, air-conditioning, refrigeration) products. Most PEP (those relevant for building assessment) are integrated into INIES database. The existence of these databases as well as the implementation of national programs to test the LCA methodology applied to buildings (*Expérimentation* HQE Performance (CSTB, 2013), E+C- (MTES, 2017)) have led the French Government to launch a new regulation (called RE 2020 for *Réglementation Environnementale 2020,* in French).

RE2020 sets progressive GHG emissions threshold values for new buildings, residential and tertiary. The thresholds concern the life cycle GHG emissions of the construction (Ic_construction) and the life cycle GHG emissions of the energy consumed during the use phase (Ic_énergie). The first indicator corresponds to the GHG emissions of the life cycle of construction products and equipment plus the emissions that occur on the construction site (energy, pumping water, etc.), during construction phase. Other indicators are voluntarily disclosed, such as GHG emissions associated with the water consumption during the use phase (Ic_eau). This regulation also sets threshold values for the energy efficiency and came into effect in January 2022 (residential buildings) and July 2022 (office and educational buildings).

The fourth pathway is related to behavior change, promoting the conscious use of equipment and would be also related to the potential rebound effects of decreasing the energy consumption of efficient equipment, such as increasing the comfort temperature because the equipment consumes less energy.

Moreover, in August 2021, the French Government signed a law imposing to the most emitting sectors to propose an emission reduction roadmap by January 2023 (Article 301, Law 2021-1104) (French Government, 2021). The buildings value chain was included in this list and, thus, it must present a clear and precise strategy for progressively reducing GHG emissions until attaining neutrality in 2050.

With regard to reducing waste, the French Government has carried out some actions over the past decade. In line with the European Directive 2008/98/EC on waste, the French Assembly approved the Act of 17 August 2015 on energy transition for green growth (*Loi de Transition Energétique pour la Croisssance Verte*, LTECV, in French), which sets a target of 70% material recovery of construction waste (MTES, 2015).

In October 2018, the law on the evolution of housing, planning and digital technology (*Evolution du logement, de l'aménagement et du numérique*, ELAN, in French) was approved, integrating specific criteria related to resources (e.g. renewable material and recycled content) for the construction of new buildings.

In 2019, the Government launched the roadmap for the circular economy, relying on actions to inform, educate and train actors to apply circular economy in their activities. Three

measures are associated with the construction sector, the first is to set sorting and recycling targets for demolition and construction phases. The second is to implement an Extended Producer Responsibility (EPR) scheme for construction and demolition wastes, which would allow the materials and equipment to be collected free of charge. The third measure is to conduct detailed pre-demolition screening to identify the potential material and equipment destinations (for recovery and reuse) (MTES, 2019).

This roadmap resulted in the passing of two particular laws. The first one concerns the anti-waste law for promoting the circular economy (*anti-gaspillage pour une économie circulaire*, AGEC, in French), approved in February 2020. AGEC law establishes the "polluter pays" principle for the construction sector through the creation of a new EPR scheme from 2023 and provides free collection of wastes that are sorted in the dedicated centers (MTE, 2021a).

Secondly, the Climate and Resilience bill (*loi climat et resilience,* in French), approved in August 2021, includes requirements on the progressive reduction of soil artificialisation for new constructions and on the energy performance level of renting buildings (MTE, 2021b).

As for water management, the water assizes program (2018-2019) (*les assises de l'eau*, in French) acted on the need to reuse water in buildings, as a means to achieve a goal of reducing water withdrawals by 25% in 15 years and set a target of tripling the volumes of non-conventional water reused by 2025 (MTE, 2020).

In the French context of sustainability issues, particularly concerning the construction sector, the Scientific and Technical Center for Buildings (*Centre Scientifique et Technique du Bâtiment*, CSTB, in French) takes a systemic approach to the socio-economic challenges of safety, health and comfort and the environment and energy, as they apply to buildings, neighborhoods and cities. CSTB plays multiple roles to support public policy decision-makers, the builders and users of buildings and the urban environment.

Especially concerning the research activities in CSTB, in 2018, the Research and Development (R&D) program to 2025 was launched, resulting in four strategic areas:

- Buildings and neighborhoods that promote harmonious living
- Buildings and cities faced with climate change
- Innovation and reliability in construction and renovation
- The circular economy and resources for construction

The first strategic area focuses on two main points: designing and retrofitting buildings so that comfort, health and safety of residents is a priority, while developing neighborhoods for harmonious living. This area covers existing buildings and new construction, with an eye to their future use.

For buildings and cities facing climate change, the objective is twofold: to strengthen mitigation and to support adaptation. For mitigation, the idea is to measure or provide tools to actors so that they can measure their carbon impact in the short, medium and long term.

The field of adaptation covers prevention, preparation for extreme events, protection of people and property during crises and anticipation of post-crisis recovery. Thus, the CSTB acts as a link between those who analyze climate indicators, those who produce data, and building designers, by providing actors with the elements (data sets, design rules) that will enable them to design and renovate in a context of climate change.

Innovation and reliability in construction and renovation is a strategic area whose objective is to provide knowledge to control the performance of thermal retrofitting activities. The actions in practice are to improve knowledge of the built stock, to measure the impact of a retrofit on uses and users, and to anticipate and support innovations in retrofitting services.

Lastly, the circular economy field focuses on identifying material flows, facilitating the recovery of materials in the existing built stock, and promoting the integration of the circular economy from the design of products, construction projects and territorial developments.

These interrelated R&D strategic areas are directly linked to the sustainability goals shown in Figure 1.5. Knowing that, among others, CSTB accompanies public authorities on the development of new regulations in France, the main motivation for stating this thesis is to support the positioning of the CSTB with public authorities on a scientific basis.

1.2 Environmental assessment of construction systems

As presented in Section 1.1, the environmental pressures exerted by the different actors have led to the development of tools to measure, calculate or estimate the environmental impacts of economic activities. In particular, for the construction sector, over the last decade, research and policies have shifted the initial focus from reducing energy consumption of buildings to a broader dimension, including other environmental issues.

In order to include other environmental aspects, several tools are available, such as environmental impact assessment (EIA), material flow analysis (MFA), life cycle assessment (LCA), rating tools and many others. Tools that focus on a particular environmental assessment are also available and used by construction practitioners for different purposes (e.g. Dow Jones Sustainability Index reporting, carbon disclosure project, etc.), such as carbon and water footprints, operational carbon emissions, measurement of on-site waste generation, and many others.

The choice of which tool to use depends on the objectives of the study, as well as the environmental issues covered by the tools. For example, water and carbon footprints focus on a single environmental impact over the entire life cycle of a product, project or system, while LCA can include as many impact categories as needed.

Rating tools are specifically created for the products or systems concerned. For example, in the construction sector, there are three main rating tools: Leadership in Energy and Environmental Design (LEED), the Building Research Establishment Environmental Assessment Method (BREEAM), and the Comprehensive Assessment System for Built Environment Efficiency (CASBEE)(Kang, 2015). These three tools are methods for evaluating and rating the environmental performance of buildings based on semi-quantitative indicators.

In some countries, particularly in the European Union (following the EIA Directive 2011/92/EU as amended by 2014/52/EU), an EIA may be legally required prior to the issuance of a building permit. The information that must be provided in the EIA concerns, for example, the resources employed to carry out the construction works as well as the disposal of waste during the construction phase, the duration of the construction works, including information on the noise, dust, odors and light emissions expected during the construction phase (European Commission, 2014).

Considering the multiple initiatives in the European Union countries, the European Commission launched in 2019 the Level(s) program. The latter is a European framework to help buildings and construction sector professionals to measure and monitor the sustainability performance of buildings within a common reference. Level(s) does not propose a new certification scheme, rather, the idea is to provide a set of reporting templates and manuals to help different construction actors in conducting sustainability performance assessments (European Commission, 2021).

An in-depth analysis of these tools is beyond the scope of this thesis, as the focus here is on LCA. The latter is a commonly used approach to assess GHG emissions over the entire life cycle of new buildings, as presented in the previous section, and is much more detailed than the rating tools and EIA. In addition, LCA avoids shifting issues between different life cycle stages, and between environmental issues.

1.3 Life Cycle Assessment – a diversity of approaches

Life Cycle Assessment (LCA) is a methodology that quantifies the environmental impacts of a product or service at all stages of its life cycle, from the extraction of raw materials to the end-of-life treatment. The main principles and requirements for carrying out an LCA are defined by the ISO 14040-44 (ISO, 2006a,b) standards. The methodological framework is built upon the four steps namely (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation, as presented in Figure 1.8.

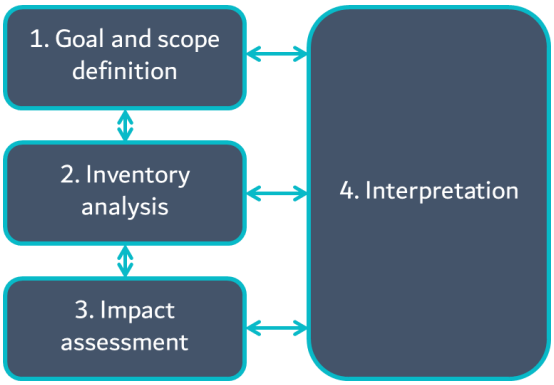

Figure 1.8 | LCA steps (ISO, 2006a,b)

Examples of using LCA in the construction sector are the existing European Standards specific to construction products (EN 15804+A2 (CEN, 2019)) and new and existing buildings (EN 15978:2012 (CEN, 2012a)), which have been used by construction product producers to declare their environmental profile and by building contractors to identify potential opportunities for eco-design. With regard to larger systems, LCA has been used to provide environmental assessment of neighborhoods and urban islets (Lotteau et al., 2015) and also whole districts (Mailhac et al., 2016).

The aforementioned European Standards are based on the attributional approach, which is also the most frequent approach applied by LCA practitioners nowadays. Although, there exists a variety of LCA system modelling approaches, each one with a defined purpose and oriented to answer a specific question (for an extensive review see Guinée et al., 2018). Table 1.1 summarizes how each approach addresses three selected methodological key points: orientation, multifunctional processes, and linking processes/suppliers. The selection of the methodological points is a combination of the reviewed criteria to compare attributional and consequential approaches recently conducted by Schaubroeck et al. (2021) and previous reviews (Guinée et al., 2018).The terminology of the approaches was taken from the 'alphabet soup' as proposed by Guinée et al. (2018). The first point consists of describing whether the approach is descriptive or change-oriented as defined by Guinée et al. (2002). The second point concerns dealing with multifunctional processes, i.e. whether the approach applies system expansion and/or substitution and/or an allocation method in a process that presents more than one function/product. The third and last key point consists of how the approach links the processes/suppliers when modelling, here the focus is to identify whether the approach considers the marginal or average processes/suppliers.

Table 1.1 | LCA approaches

Approach	Definition	Methodological key points		
		Orientation	Co-products	Linking processes/suppliers
Attributional LCA (ALCA)	Approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule (UNEP, 2011).	Descriptive	System expansion or Allocation	Average
Backcasting LCA (BLCA)	Approach in which the unit processes are linked to meet the requirements in the future, considering planetary boundaries, population growth and other constraints (Heijungs et al., 2014)	Change-oriented	System expansion or Substitution	Marginal
Consequential LCA (CLCA)	Approach in which inputs and outputs reflect the direct and indirect environmental burdens occurring as a consequence of a decision, represented by a change in demand (UNEP, 2011).	Change-oriented	System expansion or Substitution	Marginal
Decisional LCA (DLCA)	Approach in which activities are linked in a way that financial and contractual relations are respected even if the said suppliers are constrained (Frischknecht and Stucki, 2010).	Change-oriented	System expansion or Allocation	Average
Ex-ante LCA (ELCA)	Approach studying a technology that is still in its research and development (R&D) phase, where eco-design measures can be applied before market introduction (Cucurachi et al., 2018; van der Giesen et al., 2020).	Change-oriented	Not predefined	Not predefined
Integrated LCA (ILCA)	Approach that combines two or more modeling approaches such as input-output (IOA), energy scenario modeling, material flow analysis (MFA), for example, with LCA methodology (Guinée et al., 2018).	Not predefined	Not predefined	Not predefined
Macro LCA (MLCA)	Particular type of ILCA, usually applied to study incremental changes in CLCA, by using computable general (CGE) or partial equilibrium (CPE) models (Dandres, 2013).	Change-oriented	Substitution	Marginal
Anticipatory LCA (NLCA)	Non-predictive and inclusive of uncertainty, which can be used to explore both reasonable and extreme-case scenarios of future environmental burdens associated with emerging technology (van der Giesen et al., 2020)	Not predefined	Not predefined	Not predefined
Prospective LCA (PLCA)	Approach in which the technology is projected to be in a more advanced phase of development than the current situation. Forecast methods and scenario analysis are applied to study future systems (Cucurachi et al., 2018; van der Giesen et al., 2020).	Change-oriented	Not predefined	Not predefined
Dynamic LCA (DyLCA)	Approach in which the time is included to study the dynamics of the processes and of the impact assessment methods. Concerning processes, dynamic inventories are a function of time, not only during a year but also throughout the life cycle (Tiruta-Barna et al., 2016).	Not predefined	Not predefined	Not predefined
Scenario-based LCA (ScLCA)	Approach integrating scenario development method. Multiple scenarios are developed to help the decision, by identifying the trade-off between selected issues (risk, environment, cost, etc.) (Fukushima and Hirao, 2002).	Not predefined	Not predefined	Not predefined

Schaubroeck et al. (2021) have clarified the often mistaken concepts of system expansion and substitution. The former is defined in ISO 14040/44 as a way of avoiding the allocation in multi-functional processes by including all the functionalities of the system. Substitution, on the other hand, expands the system boundary in another way, by including the avoided

alternative production of the co-product (as a negative input). Figure 1.9 illustrates the possible ways of dealing with a multi-functional process consuming three resources (R1, R2 and R3) and producing two co-products (P1 and P2).

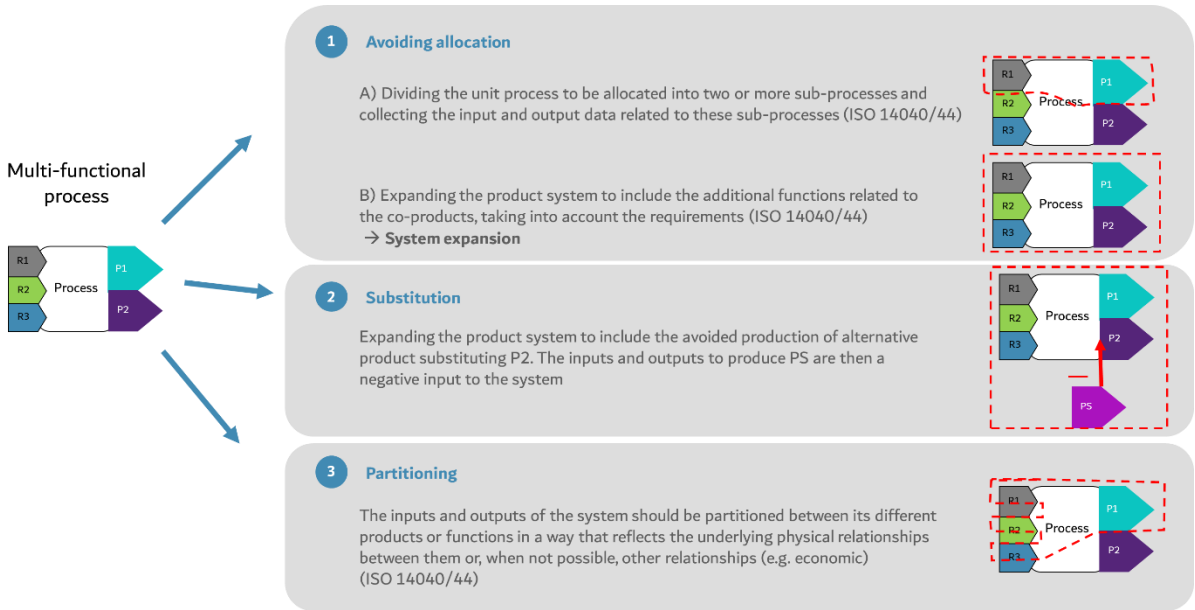

Figure 1.9 | Dealing with multi-functional processes in LCA (adapted from (Schaubroeck et al., 2021))

A combination of approaches is also possible, for example, the dynamic approach may be attributional (Head et al., 2020; Negishi et al., 2019, 2018), decisional or consequential (Collinge et al., 2018). Figure 1.10 shows some theoretical possibilities of intersections between the different LCA approaches.

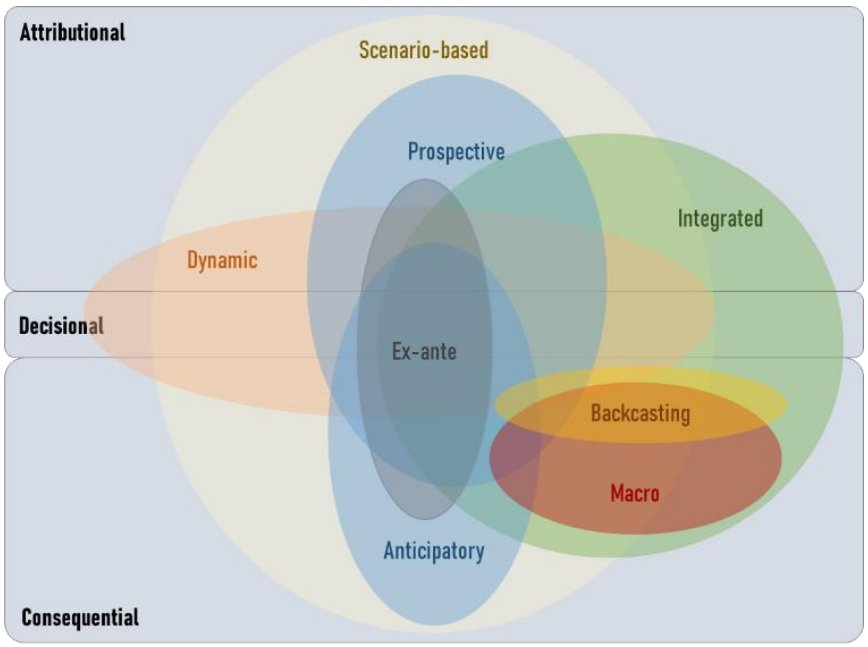

Figure 1.10 | Possible combinations of LCA approaches

The three approaches represented horizontally in Figure 1.10 are consequential, attributional and decisional. They differ from each other in key methodological points, which define the structure of the study and can be combined consistently with other approaches, with exception of BLCA and MLCA, which are particular types of CLCA.

The decisional approach is not as frequently used as the attributional and consequential ones. A Scopus search was conducted on January 2022 with the keyword "decisional LCA" and only 18 articles appeared in the results, while the same search replacing "decisional" by "consequential" had around 450 document results. When replacing it with "attributional", the number of results increased to around 500, considering that not all ALCA mention that they are attributional since it is the 'conventional' modelling approach.

Figure 1.11 illustrates some differences between ALCA and CLCA, as presented in Table 1.1. The first difference reveals how they deal with multifunctional processes. CLCA uses the substitution method as a procedure to eliminate by-products as activity outputs, where they are instead considered as negative inputs (UNEP, 2011). This is a common approach in CLCA because it presumes demand-constraint, reducing the demand for the alternative production of the co-product (Schaubroeck et al., 2021). ALCA uses the allocation (or partitioning) method for the splitting of the processes based on a defined criterion (mass, energy content, economic value, etc.). System expansion, commonly confounded with substitution in the literature, deals with multifunctional processes by considering all the functionalities of the expanded system. It is fairly discussed in the literature that both approaches are able to use system expansion (Majeau-Bettez et al., 2018; Schaubroeck et al., 2021; Schrijvers et al., 2020).

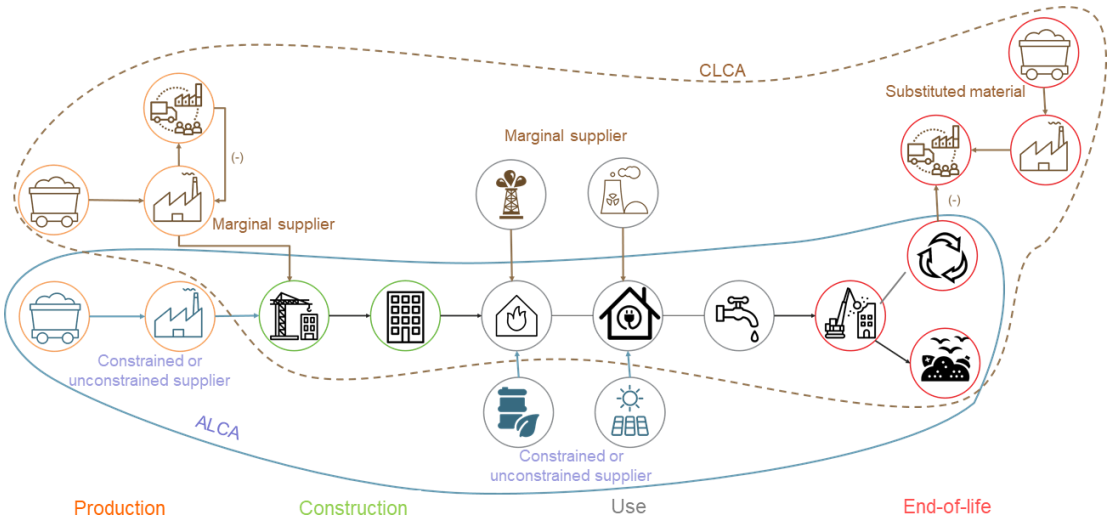

Figure 1.11 | Differences in system boundaries of ALCA and CLCA

The second difference is the marginal supplier (process) versus the average one. Marginal, in economics, means an extra unit, for example, marginal product means the extra amount of output the firms get from an extra unit of a defined input (Mankiw, 2009). In the

context of LCA, marginal processes are those that react to the studied change in demand, not necessarily the normative linked ones (Brandão et al., 2017).

Recently, Schaubroeck et al. (2021) studied the different interpretations of the product system in ISO 14040-44 and in the UNEP's guide (UNEP, 2011) for CLCA. In ISO 14040-44, a product system studied in CLCA coincides with the product life cycle, i.e., includes the normative life cycle interlinked processes of a product. On the other hand, for UNEP (2011), the "*systems analyzed in these LCAs are made up only of processes that are actually affected by the decision, that is, that change their output due to a signal they receive from a cause-and-effect chain whose origin is a particular decision*". This means that the interlinked processes of some (or all) life cycle phases can be left outside the system boundaries if they are not supposed to change because of the decision.

For example, the CLCA product system considered the decision to buy a new house that was already built before the moment when the decision was taken comprises all life cycle phases of a house (raw materials extraction, transport, production, use and end-of-life) for ISO 14040-44. On the other hand, according to UNEP (2011), the product system considers the usage of the house and the market responses to produce other houses that are related to this decision (and the respective life cycle stages).

Definitions of CLCA

Considering that the ISO 14040-44 standards do not present a clear definition of consequential and attributional approaches, Schaubroeck et al. (2021) recently reviewed the definitions that appear in the literature following the four criteria: logic (no contradictions), name (linkage with the concept), consensus (the concept is supported by a broad community) and application. The authors retained two definitions that would adhere to the four criteria: the one from the International Life Cycle Data System (ILCD) handbook (EC-JRC, 2010) and the one proposed in the Global Guidance Principles for LCA Databases from the United Nations Environmental Programme (UNEP) (UNEP, 2011), both are presented in Table 1.2.

Table 1.2 | CLCA definitions

Source	Definition
(UNEP, 2011)	*"System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for functional unit"*
(EC-JRC, 2010)	*"It aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy, both in the analyzed system's background system and on other systems. It models the analysed system around these consequences. The consequential life cycle model is hence not reflecting the actual (or forecasted) specific or average supply-chain, but a hypothetic generic supply-chain is modelled that is prognostizised along market- mechanisms, and potentially including political interactions and consumer behaviour changes"*

In this thesis, the definition from UNEP (2011) is chosen as the most appropriate, due to the fact that UNEP is a global institution and, therefore, the consensus reaches a wider

community. Besides, the UNEP definition is more generic and broad and the term 'change in demand for functional unit' relates directly to the perturbation in economic modelling. However, the EC-JRC definition would also cover our understanding of consequential LCA, as the large-scale perturbation occurring in the foreground system has consequences going beyond the background system, including interactions among other institutional sectors, affecting also households behavior.

Moreover, also concerning definitions and the concepts behind them, Schaubroeck et al. (2021) found that there are still misconceptions of what CLCA means. They identified a few recent studies wrongly considering that CLCA is theoretically only appropriate for studying large-scale changes, as indicated in the International Life Cycle Data System (ILCD) handbook (EC-JRC, 2010). The authors argue that the choice of one approach over another is related to the purpose of the study, not the magnitude of change.

1.4 CLCA applied to the construction sector: a literature review

The research was conducted in December 2021 using Scopus and Google Scholar as the main research tools. Scientific articles, thesis and other studies in both English and French were included in this review. The buildings and construction sector is particularly related to other sectors. For that, the research may include other sectors, such as the energy sector, when the studies assess energy consumption or energy efficiency in buildings. The search keywords were "consequential life cycle assessment" AND "construction sector", OR "construction products", OR "buildings", OR "buildings eco-design", OR "circular economy".

For the cases where two or more papers are associated with the same research project, e.g. parts 1 and 2 of the same case study or presentation of partial results in a conference (proceedings paper) followed by the presentation of final results in a journal article, they were accounted for only once, though all grouped papers are cited. Therefore, forty-three studies were selected for pursuing the review.

For conducting the review, the selected criteria are the LCA methodological choices of the studies, which are listed here below:

- Purpose
- Scale and time horizon
- Combination with other LCA approaches
- Method for identifying the affected suppliers
- Rebound effects
- LCIA methods
- Uncertainty and sensitivity analysis

The following sections detail the approach of each criterion applied here in this article.

Fields

As explained previously, the construction sector is a wide field, covering a diversity of subjects. The subjects included in this research are presented in Table 1.3.

Table 1.3 | Subjects included in the review

Subject	Description
Construction systems	Materials that are combined to compose the elements of a building – it includes all studies that analyzed a construction product in particular (for example, steel or wood).
Circular economy	Reusing or recycling existing construction materials and products (also known as cascading for wooden products).
Cement industry	Processes involved in the improvement of cement production.
End-of-life	Processes that are specifically associated with the end-of-life of buildings, construction products and equipment (waste collection, disposal, recycling). However, they do not close the loop as in circular economy studies.
Thermal retrofitting	Activities performed in the buildings (residential or tertiary) to improve their energy efficiency.
Energy mix	Evolution of energy mix processes integrated to building energy consumption.
Building eco-design	Measures to improve the environmental performance of buildings.
New policies	Large-scale implementation of actions (at national or continental level) to promote sustainable buildings.
Road pavement	Materials and processes involved in constructing the road for vehicular traffic.
Brownfield rehabilitation	Activities associated with revitalizing post-industrial sites by removing the presence of hazardous substances and contaminants.

Figure 1.12 presents the findings of this review. The most frequent subject that appears in the reviewed articles is the comparison of the environmental performance of two or more construction products or/and systems that fulfill the same requirements/functions. When comparing construction systems, the most popular topic is to investigate the potential substitution of concrete-based with timber-framed systems. This may be explained by the fact that increasing wood-based constructions is included in the goals of main national strategies for reducing GHG emissions.

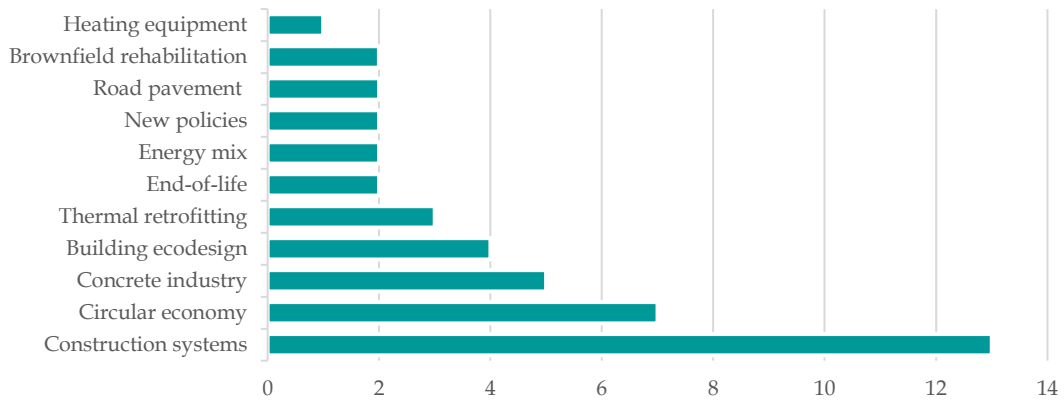

Figure 1.12 | Subjects of reviewed studies

The second most popular subject is the circular economy, which could be associated with other listed subjects in Table 1.3 as well. Here, we considered as circular economy the studies that analyze the reuse of construction products in a second life and further. Two cases where concrete was reemployed were included in this classification, even though they have also an impact on the cement industry.

The concrete industry, the third most popular topic, appears interested in studying the alternative raw materials that suggest a better environmental footprint, such as using copper or steel slag to substitute sand.

Building eco-design appeared in the studies that used a CLCA for improving the environmental performance in the design phase of new buildings. Two of them studied the construction of net zero energy building (NZEB) from the consequential point of view (Collinge et al., 2018; Frossard et al., 2020). The other two studied the strategies for optimizing the environmental profile of dwellings in Belgium (Buyle et al., 2018a, 2014).

Thermal retrofitting was the subject of study of three articles. One focused on identifying the priorities for refurbishing office buildings in New Zealand (Ghose et al., 2019), the other one, also in New Zealand, studied thermal retrofitting in residential buildings, but with a focus on the resource and waste management (Ghose et al., 2017). The third one was interested in the cost, integrating a Life Cycle Costing (LCC) of the retrofitting works in their study (Pedinotti-Castelle et al., 2019).

Two articles studied the effects of studying the end-of-life through the consequential perspective. Vieira & Horvath (2008) and Sandin et al.(2014) were interested in the methodological implications of assessing the end-of-life of buildings from the consequential perspective.

The energy mix was studied by Roux et al. (2016, 2017) and also in the main author's thesis. The more recent article studied electricity system modelling, coupling a dynamic approach to the marginal supplier identification. The less recent focused on the evolution of the energy mix and the impact of that on the CLCA of the buildings.

The two studies that were included in the new policies subject are the one from Kua (2015) and the article from Eriksson et al. (2011). The first one studied the integration of a new policy to replace the sand by steel slag in the construction products. The second one studied the increased wood use in the European construction systems.

Road pavement was studied in two journal articles. The more recent, from Azari Jafari et al. (2019) studied the substitution of asphalt with concrete for traffic service over the entire network of the two-lane roads in Quebec. The second one, from Mladenovi et al. (2015), studied two options of materials for asphalt wearing courses.

The two studies interested in brownfield rehabilitation are the two-part articles from Lesage et al. (2007a,b) (here considered as one result) and the one from Hou et al. (2018). The

latter quantified the mitigation potential on a city level of rehabilitation of brownfield land, including 206 contaminated sites. The articles from Lesage et al. (2007ab), studied the legal and appropriate management of legacy contamination on 1 hectare of the tracked brownfield land rehabilitation.

Finally, one study was focused on the heating equipment, namely heat pumps. The article provides carbon dioxide emission factors of district heating from ground source heat pumps in Finland, based on hourly data at present and in various future scenarios (Rinne and Syri, 2013).

1.4.1 Purpose for choosing consequential approach

Here "purpose" stands for the motivation for using the consequential approach. The authors do not usually explicitly mention this information when choosing the attributional approach; however, in consequential assessments, they often justify their choice. Figure 1.13 presents the purposes identified in this review.

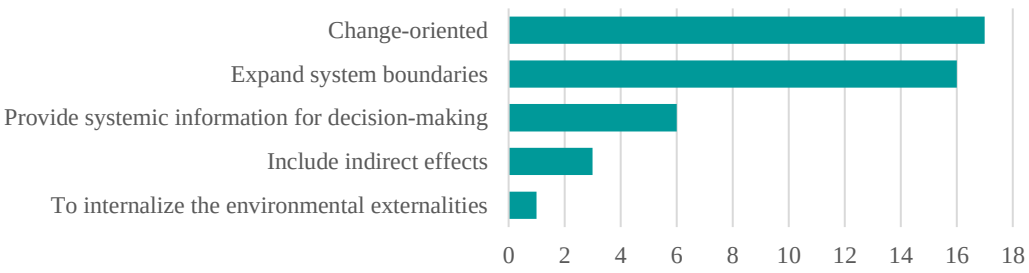

Figure 1.13 | Purpose of CLCA

Considering that CLCA is a change-oriented approach, authors that study a change do not necessarily justify their choice for a consequential approach. This is the case for seventeen of the reviewed studies, either they do not justify their choice for a consequential approach because they state that CLCA is the pertinent choice for studying changes; or they explicitly mention that this is the purpose for choosing the CLCA in their study.

The other purposes are detailed in the following paragraphs.

Expanding system boundaries

Overall, sixteen studies justify the choice for a consequential approach to go beyond and expand the usual system boundaries of ALCA to also include the substitution effects. It is worth mentioning that the expansion of system boundaries in this case corresponds to the second case illustrated in Figure 1.9. The reviewed studies are interested in studying the avoided impacts that would occur in the case of replacing a conventional construction product or system with a new one, or even still to assess different possibilities of production pathways.

Forster et al.(2019), for example, studied the deployment of the recommendation from the United Kingdom Committee on Climate Change to build all new housing in timber frame. The authors included the substitution of mineral construction materials by timber-framed ones and also the fossil fuels replaced by biomass energy. The authors found that the avoided impacts from these two sources can be significantly offset by the displacement of the initial function of the land (before conversion to meet the new demand).

Skullestad et al. (2016) studied the implications of changing the construction system of a high-rise building from concrete to timber and concluded that timber structure is less impacting in all scenarios mainly due to avoided emissions from the wood burned with heat recovery to replace natural gas.

Kua (2015) and Turk et al. (2015) compared different raw materials to produce concrete. Kua (2015) was interested in studying the implications of a new policy fostering the employment of steel slag as a replacement for sand as an aggregate. The author estimated the trade effects in Singapore, i.e., the reduction of sand import and increase in export and the increase in demand for secondary steel-making technologies. The author found that the environmental benefits of substituting sand with steel slag depend on the assumed steel-making technology, which can be more environmentally efficient when adopting improved processes. Consequential approach highlights the potential benefits when including the trade effects while the attributional assessment shows that sand is less impacting independently from the steel-making technology.

Turk et al. (2015) studied the use of fly-ash as a binder replacing cement and the use of foundry sand, recycled aggregate, and steel slag replacing aggregate. These alternatives are called by the authors "green concrete". According to the authors, the consequential approach highlights the benefits of avoiding the disposal of the waste materials, and the long distances to deliver these secondary materials do not influence the results when compared to the conventional option.

Other examples are provided by Kua and Maghimai (2017), who studied replacing structural steel with reinforced concrete, and Mladenovi et al. (2015), who studied the employment of steel slag in road pavements. Both concluded that the substitute benefits depend on the transportation distances. Moreover, four articles compared a potential substitute that would be supposed to reduce the environmental impacts and found that the substitute is actually more impacting than the conventional material/system. This was the case of Kua and Lu (2016), who evaluated the impacts of replacing the tempered glass with polycarbonate, Kua and Kamath (2014), who studied the replacement of concrete by clay bricks and Kua (2013a, 2013b), who studied the substitution effects of copper slag replacing sand in concrete mixtures.

Systemic information for decision-making

According to ISO 14040/44, LCA provides support to help decision-makers for different purposes (ISO, 2006c), thus, regardless of the modelling approach, LCA is intrinsically a methodology for decision-making. Nevertheless, six studies justify their choice for a consequential approach to support decision-making. Among the different mentioned types of decisions, four studies make clear that CLCA is needed when a decision involves a new policy. According to Taufiq-Fauzi et al (2021), decisions including the implementation of a system on a large-scale should not be neglected, such as in urban planning policies. According to Buyle et al. (2018a) decisions in eco-design and policymaking should use a CLCA because they suggest changes in future production, thus, they are change-oriented by nature. For the authors, consequential modelling is complementary to the ALCA and is a useful addition for decision-makers. Sacchi (2018) and Kua (2015) also mention the importance of CLCA for policy design.

Other types of decisions appear in the literature. Roux et al. (2016) use as an example the decision of renovating or constructing a new building, and Vieira & Horvath (2008) state that decisions to buy or not to buy a product should be based on CLCA.

Indirect effects

Three studies justify the choice of using a consequential approach for considering what they call "indirect effects". This is a broad term with different meanings for each author. AzariJafari et al. (2019) consider indirect effects like the changes in the fuel market and consumer behavior caused by pavement substitution. This is because the type of pavement has an influence on the fuel consumption of road transportation and also in the electricity consumption in the buildings due to the albedo effects.

Buyle et al. (2019) considered as indirect effects the indirect trade effects, i.e. the suppliers who are actually affected are taken into account. According to the authors, from the circular economy point of view, this is particularly relevant since fostering circular building alternatives must be environmentally responsible.

Lesage et al. (2007a,b) and Hou et al. (2018) use a consequential approach so that the relative significance of primary, secondary and tertiary impacts of brownfield rehabilitation can be assessed. Indirect effects would be what the authors call "tertiary impacts" and stand for the redevelopment and residential occupation of the tracked site, i.e., if the recovered site is used for housing, the tertiary impacts are building houses and the housing services that occur on-site, as well as the avoided construction in suburban greenfield and the respective housing services that would occur there. Primary and secondary effects are assessed with an attributional approach as well.

Internalize environmental externalities

According to Pedinotti-Castelle et al. (2019), the costs are an important element for decisions in retrofitting. However, although the primary intention of policies is to include externalities, the environmental impacts are often not internalized as a cost. The authors justify the use of consequential modelling for this purpose so that the environmental benefits would be more apparent.

1.4.2 Scale and time horizon

The change may present different sizes that will affect the market parameters differently. A small-scale change may be defined as the change that does not affect the overall market parameters, such as the market trend or constraints in production whereas large-scale would affect them.

The general guide of the International Reference Life Cycle Data System (ILCD) provides a rule based on the annually installed capacity for considering a change as "small" or "big". If the annual additional demand is larger than the usual annually replaced installed capacity, it is considered a large-scale change (EC-JRC, 2010). For example, assuming that an installation has a lifetime of 20 years, its annually replaced installed capacity is thus 5%. If the traded product is produced at 1000 tons/year, any change larger than 50 tons/year would be considered large-scale because it exceeds the replacement capacity of the installation. This guide also provides a decision tree for choosing the most appropriate approach in function of the scale and time horizon of the studied change. For marginal changes, the authors recommend an attributional approach, while for large-scale changes, a consequential approach is to be favored.

Concerning time horizon, short-term changes affect only capacity utilization while long-term changes would also affect capital investment, for example when installing new facilities (demand increase) or deactivating installations (demand decrease) (EC-JRC, 2010; Weidema et al., 2009). Large-scale (or non-marginal) changes will usually affect capital investment and are thus also long-term.

According to this review, eighteen studies mentioned the size and the time horizon of the studied change. When not declared, the size of the change was interpreted as small for small quantities of a construction products or marginal construction sites. According to Figure 1.14, thirty-nine studies assessed only small-scale changes, two only large-scale changes and two a combination of sizes of changes.

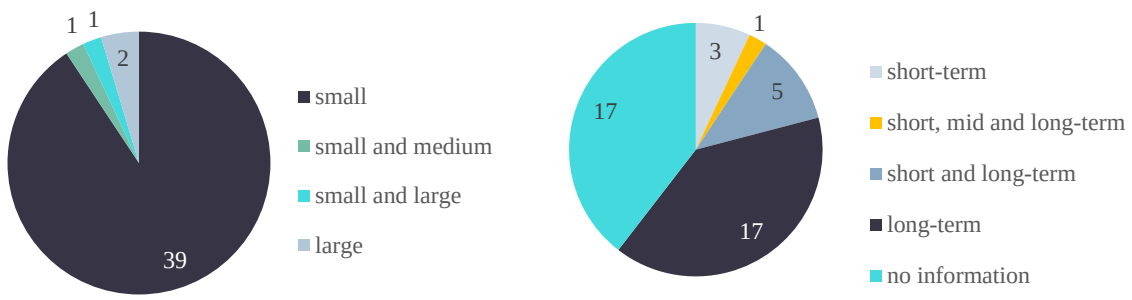

Figure 1.14 | (a) Scale of the change (b) Time horizon

The two studies that assess a large-scale change are Eriksson et al. (2011) and Cordier et al.(2021). The first one studied the massive substitution of concrete by wood in two scenarios: 1 million apartments per year in Europe and consumption of 1m^3 *per capita* of wood in 2030. Cordier et al. (2021) studied the increasing use of wood structures for non-residential buildings in the province of Quebec, by assuming that the constructions in concrete and steel would be substituted by wood-frames.

The studies that mix scales (small and medium and small and large) are Buyle et al. (2018) and Rinne & Syri(2013), respectively. The former declares that only small and medium scale changes in demand are considered in their study. Rinne and Syri (2013) study the small-scale change of adopting the change in heating equipment, and extrapolate the change to large-scale technologies.

Concerning the time horizon, seventeen studies do not mention whether they are considering short or long-term changes. It is often mentioned the long lifespan of the construction products and systems, however, no mention of what type of consequences they assess.

When the time horizon is declared, the most usual is to assess only long-term consequences (Figure 1.14b), which is the most typical and dominating effect according to Weidema et al. (2009) and it is also the assumption of the Ecoinvent consequential database. Six authors studied more than one time-horizon (long-term and mid- and/or short-term), five of them implemented a scenario analysis and found that the results are sensitive to time horizon (Kua, 2015; Kua and Kamath, 2014; Kua and Lu, 2016; Kua and Maghimai, 2017; Rinne and Syri, 2013). AzariJafari et al. (2019) used a dynamic approach and shifted from short to long-term suppliers over time (e.g. electricity supplier was changed in 10 years). The challenge found by authors was to define the frontier between short and long-term periods and proposed a sensitivity on this matter.

Finally, three authors studied only a short-term change (Frossard et al., 2020; Gomes et al., 2019; Roux et al., 2017). Gomes et al. (2019) justified the choice for assessing only short-term effects because the existing capacity can absorb the changes in demand. Frossard et al. (2020) followed the method developed by Roux et al. (2017), which does not take into account

the long-term effects of future installed power plant capacities. The latter demands a prospective scenario integration, which is pointed out as relevant for future research.

1.4.3 Combination with other LCA approaches[4]

As explained in the previous section, there exists a large variety of LCA approaches in the literature. This reviewing criterion aims at identifying the studies that couple another approach with CLCA. In section 1.3, Table 1.1 Table 1.2 sums up the different LCA approaches.

This review found twenty studies that compare their results from both CLCA and ALCA perspectives. Seventeen found significant differences in the results, leading to different conclusions. The most common reasons for the differences are the marginal suppliers that are often the most impacting (in the energy mix for example) and the avoided impacts due to substitution effects. For example, Kua and Kamath (2014) found that the fired bricks are more impacting than concrete according to the ALCA results, however, from CLCA results, concrete is more impacting, but not significantly. Roux et al. (2016) found that electric heating is less impacting than gas heating according to ALCA while CLCA inverses this conclusion because of marginal suppliers.

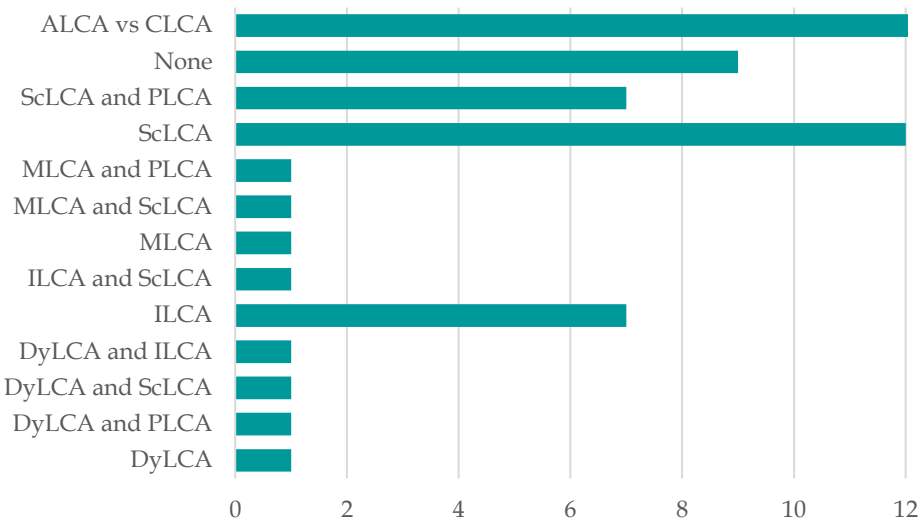

Figure 1.15 | Combination with other approaches

Figure 1.15 presents the results of this review with regard to the combination with other LCA approaches, as explained in section 1.4.3. These results show that the most common approach is to combine ScLCA with CLCA through coupling a scenario analysis for dealing with the uncertainties of consequential modelling and also to provide more robust results for

[4] ScLCA: Scenario-based LCA, ILCA: Integrated LCA, MLCA: Macro LCA, DyLCA: Dynamic LCA, PLCA: prospective LCA

decision-making. For example, Prateep Na Talang et al. (2017) proposed nine scenarios to compare possible routes for producing fired bricks in the future, three of them under consequential modelling. Buyle et al. (2018) used a ScLCA to compare the performance of different types of exterior cladding, considering the thermal performance and service life and Buyle et al. (2014) chose three optimization scenarios for helping decision-makers to prioritize design improvements (selecting insulation materials, increasing the insulation thickness and changing the heating system).

Seven works used a ScLCA and PLCA to study possible trade effects of technological developments of construction products and systems (Kua, 2015, 2013b; Kua and Kamath, 2014; Kua and Lu, 2016; Kua and Maghimai, 2017; Mladenovi et al., 2015; Turk et al., 2015). Kua and Kamath (2014) studied two possible substitution scenarios, where they changed the percentage of concrete being replaced by bricks, and two likely scenarios of the reactions in international trade in Singapore. Kua (2013a,b) studied three likely scenarios of the trade effects associated with the increase in demand for copper slag as a replacement for ordinary Portland cement, i.e., three possible destinations for the excess of cement.

Kua and Maghimai (2017) and Kua and Lu (2016) studied short and long-term consequences, where a short-term change in trade implies no change in import or export of the replaced product and neither an increase in demand for the new product. The long-term change in trade includes market speculation, i.e., other sectors will react to the excess of the product on market, and the market will adjust itself to the changes in demand for the products. Kua (2015) added, as well, the mid-term change in trade, which implies that the market is adapted to the decrease in demand for the replaced product, therefore, the excess of it does not affect the other sectors and is exported.

This review found one project that combined the CLCA with ScLCA and MLCA approaches. Lesage et al. (2007a,b) studied three scenarios based on their likelihood of avoiding new constructions elsewhere resulting from the rehabilitation of the brownfield site. The authors coupled a simplified partial equilibrium model to identify the marginal urban and suburban markets for housing services in the most probable scenario (in which they assume that new construction in the rehabilitated brownfield avoids new buildings and housing services in a combination of suburban and urban sites).

Two studies coupled a computational equilibrium model to the CLCA and were considered as MLCA. Gomes et al (2019) used a general equilibrium model (see Glossary) to identify the markets that are affected by the technology changes projected to 2050 of cement production in Brazil (thus, they also combined a PLCA).

Eriksson et al. (2011) coupled a global partial equilibrium model (see Glossary) of the forest sector (namely the model called EFI-GTM[5]) (Kallio et al., 2014) to obtain the projected

[5] Global Trade Model (GTM) developed by the European Forest Institute (EFI)

market equilibrium prices and volumes for wood products. The authors studied four different scenarios of the increased use of wood in the construction sector over the period from 2008 to 2030. The first scenario considered a growth rate of wood consumption slightly below 1% annually up to 2030. The second considered the substitution of concrete by wood gradually increasing to 1 million apartments in 2030, based on data from a Swedish case study, and the third considered the same assumption as the second, but used data from a case study in Finland. Finally, the fourth scenario considered that European countries will gradually increase their consumption of wood up to 1 m^3 *per capita* in 2030.

This review found nine studies that can be considered as ILCA. Four of them use a Life Cycle Costing (LCC) (Buyle et al., 2019; Pedinotti-Castelle et al., 2019; Sanchez et al., 2019; Taufiq Fauzi et al., 2021) to integrate the economic feasibility of the compared solutions.

Forster et al. (2019) combined a carbon model and an MFA to study the environmental balance of expanding wood consumption for construction purposes. Prosman and Sacchi (2016) combined CLCA with the environmental supplier selection criteria (E-SSC) method, which is a systematic method for selecting suppliers in a forward supply chain. The authors developed an E-SSC for circular supply chains in the construction sector. Lastly, Vieira and Horvath (2008) used an Input-Output analysis (also called Hybrid LCA) to assess the environmental impacts associated with the end-of-life of buildings.

One study (AzariJafari et al., 2019) combined the CLCA with DyLCA and PLCA. The authors proposed a dynamic LCI to take into account the time-dependent parameters, such as installation capacity for production, carbonation, fuel consumption, electricity consumption, etc, over a road pavement lifecycle, proposing a technological change where jointed plain concrete pavement replaces asphalt pavement.

1.4.4 Method for identifying the affected suppliers

There is a variety of methods to identify and quantify the activities that are impacted by a change in demand (Yang and Heijungs, 2018). The most currently cited work in the literature is the step-wise method proposed by Weidema (2003), with 5 steps, and revisited in 2009 by Weidema et al. (2009), with four steps.

It is also common to use an economic model, which is a generic term to define a mathematical framework that intends to hypothetically describe the real economic interactions by using a set of mathematical variables and equations (Mankiw, 2009). In CLCA, they are often used to model the supply and demand responses to marginal changes, either considering linear or nonlinear relationships (Dandres, 2012; Wood and Hertwich, 2013; Yang and Heijungs, 2018).

More sophisticated models, such as computable equilibrium models (general – CGE; or partial - CPE) are generally coupled to CLCA to quantify the economic activities that are affected by the studied change, including also the so-called economy-wide rebound effects

(Dandres, 2012; Ekvall, 2002). More details on these models and the reasons for coupling them with LCA are presented in Chapter 2.

Figure 1.16 presents the results of this review. The most common method applied to identify the suppliers that are actually affected by the proposed change is the use of the stepwise method from Weidema et al. (2003, 2009). When the authors used the Ecoinvent consequential database for obtaining the background data, which is based on this method, it was also accounted for as using this stepwise method.

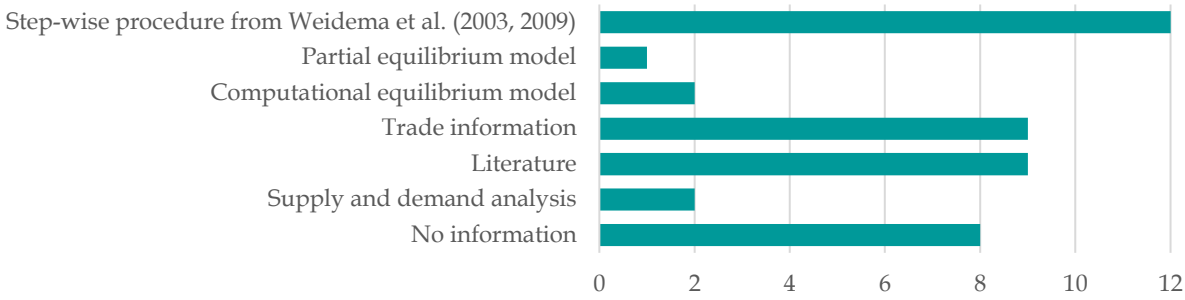

Figure 1.16 | Methods for identifying affected suppliers

The three studies that couple an equilibrium model (partial or general) to CLCA use it for identifying the affected technologies/suppliers. Lesage et al (2007a,b) apply their partial equilibrium equations by using the price elasticities of urban housing services to obtain the affected areas of urban and suburban sites/greenfields.

Eriksson et al (2011) and Gomes et al. (2019) coupled a computational equilibrium model (partial and general, respectively) in their study. The idea behind both studies is to equilibrate the supply and demand of all commodities after a shock (increase in demand for wood in the first and increase in demand of 1 ton of cement in the second) and identify who are the actual suppliers, based on market prices and elasticities. One could say that these models could be also considered trade-based because both include a trade database.

Nine studies were considered as using trade information to identify the marginal suppliers. For example, (Kua, 2015, 2013b; Kua and Kamath, 2014; Kua and Lu, 2016; Kua and Maghimai, 2017) used information from national stockpiles, main traders, and national production of the respective construction products in Singapore. Two studies propose a new method for identifying the affected suppliers based on trade. Sacchi (2018) proposed some adaptations to the aforementioned stepwise method. In addition to the market trends, the author included the trade information (import and export of the commodity) and the capability of the domestic production and imports to absorb the shock. The proposed method was applied to an increase in demand of 1 ton of cement in Canada, Japan, and France.

Pizzol and Scotti (2017) proposed a method for identifying the marginal suppliers of wood products. For that, the authors use a trade network analysis, which is fed by trade information (amounts of wood imported/exported between countries) from the Food and

Agriculture Organization of the United Nations, statistics division, (FAOSTAT) database (FAOSTAT, 2016).

Nine of the reviewed studies use information based on the literature review for identifying which technology will be affected by a change in demand. Tanguay et al. (2021) used a method developed by (AzariJafari et al., 2019) and Frossard et al. (2020) used the method developed by Roux et al. (2016). Khan et al. (2021) used the report of the national strategy on energy in Finland for identifying the marginal energy mix; Roux et al. (2016) assumed that marginal electricity is the most expensive and natural gas is the marginal technology for heating; Sandin et al. (2014) defined possible future scenarios for the affected technologies based on literature (e.g. wind power replaces diesel for demolition purposes, then it would be the marginal technology); and Skullestad et al. (2016), who assumed that the marginal Norwegian electricity supplier is an average European mix.

Finally, two studies used a supply and demand analysis to consider either full-elasticity of supply (Faraca et al., 2019) or full-constraint of supply (Arrigoni et al., 2017).

1.4.5 Rebound effects

According to the ILCD handbook (EC-JRC, 2010), the environmental consequences assessed by a CLCA are divided into primary and secondary consequences. The first one concerns the direct consequences caused by a marginal change, obligatory in a CLCA, and the second one are the rebound effects, which are optional to include.

Rebound effects are defined as the derived changes in the overall production or consumption caused by (un)expected responses from systemic factors, such as money, time, technology, and space (Font Vivanco and van der Voet, 2014; Weidema, 2003). Table 1.4 presents the definitions of "first", "second" and "third-order" effects provided by three studies that are commonly cited in the literature, from energy, transport and information and communications technology (ICT) fields.

Table 1.4 | Definitions of degrees of rebound effects found in the literature

Authors	Field	First order	Second order	Third order
(Greening et al., 2000)	Energy	Direct rebound, or 'pure price', effects An improvement of energy efficiency drops the price of the energy service and thus increases the demand for the same source of energy, at a micro-level.	Indirect rebound, or secondary, effects The consumers save money because an energy service is less expensive (due to higher efficiencies) and spend it on other goods and services, this is called indirect rebound effects or 'secondary effects'.	Economy-wide, or 'market-clearing price and quantity Effects that occur at a macro-level, considering the changes in prices and quantities in other economic sectors. Transformational effects Technological improvements in efficiency affect social institutions and change the production structure, with a long-term perspective.

(Berkhout et al., 2000)	Energy	First-order rebound effects Direct price and income effect of an improvement in efficiency, for the consumer and the producer.	Second-order rebound effects Indirect price and income effect of an improvement in efficiency, for both consumer and producer.	Third-order effects Structural effects from the shift of the pattern of sales of the production sector.
(Hilty et al., 2006)	ICT	First-order or 'primary' effects Related to the physical existence of the product	Second-order or secondary effects Indirect effects resulting from the ability to change processes	Third-order or tertiary effects The medium or long-term effects from the creation of structures and behavioral adaptation
(Sandén and Karlström, 2007)	Transport	First-order consequences Relations between the use, production and waste handling of a product	Second-order consequences Include the economic flows related to the physical flows, i.e., the constraints, negative feedbacks and equilibrium adjustments obtained from price mechanisms	Third-order or tertiary effects Include the radical and irreversible changes in systems through learning effects and positive feedbacks

Therefore, this criterion was included to investigate how and in which context these effects have been assessed in the CLCA studies.

As presented in Table 1.5, the majority (thirty-three out of forty-three) of the reviewed studies do not mention rebound effects as presented in Table 1.4. Some authors suspect that the studied change triggers important rebound effects, however, due to time constraints, they suggested it as a perspective for future research (Gomes et al., 2019; Sacchi, 2018).

Table 1.5 | Rebound effects

	Number of studies
No mention of rebound effects	33
Maybe included by a computable equilibrium model	1
Assessed	7
Not assessed	2

Except for Buyle et al. (2019), the other two authors that justified the choice for the consequential approach as including indirect effects assessed rebound effects in their studies. AzariJafari et al. (2019) included the consumer behavior on fuel consumption related to the increase of fuel efficiency and changes in cooling and heating demand due to the contribution of road pavements to the urban heat island effect (albedo effect), which can be considered as secondary effects from Greening et al. (2000). And second-order rebound effects from Berkhout et al. (2000). Lesage et al. (2007a,b) included three scenarios to take into account the development and future occupation of the recovered brownfield resulting in avoided occupied areas and consequently avoided housing services elsewhere. A partial equilibrium model was used to estimate the effects on supply and demand for housing services, by using

price elasticities from literature. These effects can be considered as the transformational effects from (Greening et al., 2000) and/or the third-order effects from (Hilty et al., 2006).

More recently, and inspired by the work conducted by Lesage et al (2007a,b), Hou et al. (2018) studied the environmental impacts of rehabilitating brownfields in San Francisco, United States. However, unlike the previous study, the authors assumed for the so-called 'tertiary impacts' that the benefit from brownfield redevelopment lies in avoiding the development of suburban greenfields, and thus they did not conduct a partial equilibrium model based on the supply, demand and price elasticities as Lesage et al. (2007a,b). For the purpose of their calculations, the authors did not consider the industrial and commercial use of suburban greenfields, the tertiary impacts being mostly residential energy consumption and commuting(Hou et al., 2018). According to their results, these tertiary impacts represent the great majority of the GHG emissions reductions, in all studied scenarios, and the benefits correspond to 14% of the annual city's GHG emissions.

Moreover, Kua and Maghimai (2017), Kua and Lu (2016), Kua (2015) and Kua and Kamath (2014) included in their studies a scenario of consequences where the increased demand for a construction product is constrained (usually supplied by national stockpile) inducing the increase of import of this product. According to the authors, this is a second-order effect from Sandén and Karlström (2007).

1.4.6 LCIA methods

According to Weidema et al. (2003), most LCIA methods are consequential since they calculate the impact corresponding to a marginal emission, rather than the average consequences of all emissions and resource consumption. Despite this, this criterion was integrated into the current review for two reasons: investigate studies that adapt the existing methods to include marginal characterization factors; and to identify the impact categories (midpoint/endpoint, single score) that have been studied by CLCAs in the construction sector.

Concerning the LCIA methods selected by the reviewed authors, Figure 1.17 presents the results found in this review concerning the number of studies choosing the LCIA method by year of publication. The studies that are considered as non-applicable (NA) are the ones that do not conduct an impact assessment either because they propose a method for obtaining the consequential LCI or because they present the results in terms of substance emissions rather than impact categories. An important number of studies (17%) do not declare the LCIA method used in their assessment. This happens mainly for the studies that present their results for global warming potential and embodied energy.

As Figure 1.17 shows, the most frequent methods for analyzing the results are ReCiPe, developed by Goedkoop et al. (2009) and updated in 2016 (Huijbregts et al., 2016); and the method developed by the Institute of Environmental Sciences of Leiden University (CML).

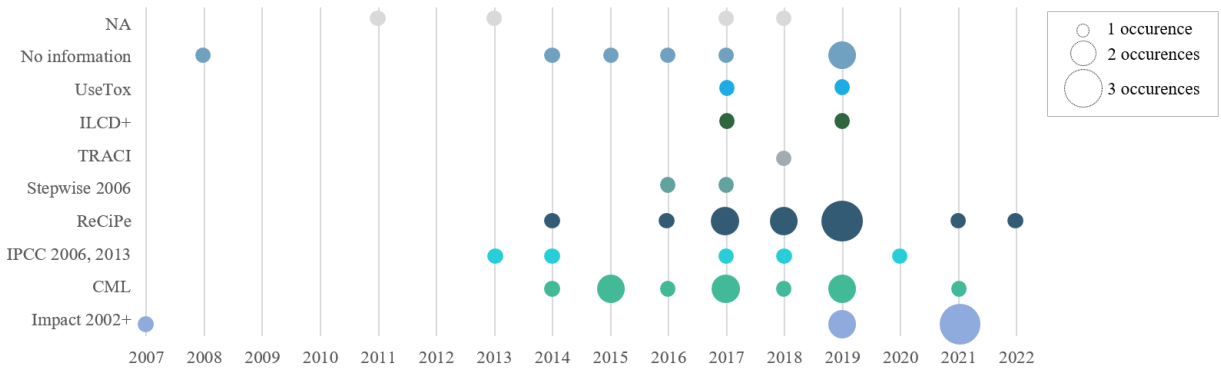

Figure 1.17 | LCIA methods in the reviewed studies

Six out of eleven of the studies using ReCiPe chose the hierarchist cultural perspective (ReCiPe H), which is based on the scientific consensus of timeframe and plausibility of impact mechanisms and is often considered as the default perspective among practitioners (Huijbregts et al., 2016). Buyle et al. (2014) chose to use the egalitarian perspective, which, according to the authors, is the most precautionary because the long-term emissions are fully included increasing the completeness of the results. The other four studies that use the ReCiPe method do not specify the chosen perspective.

Impact 2002+ was chosen by six studies, being the third most frequent method applied by the reviewed studies. One of them justified their choice by saying that this method covers many substances and models in both midpoint and endpoint indicators. Lesage et al. (2007b) applied Impact 2002+ and pointed out some limitations related to this method when analyzing their results (e.g. lack of characterization of land transformation and low covering of substances for Ecotoxicity).

The Tool for the Reduction and Assessment of Chemical and other environmental impacts (TRACI) assessment method was used by one study (Collinge et al., 2018). The authors justify their choice by the feasibility of integrating the characterization factors with their dynamic LCI results.

With regard to the level of characterization of the impacts, this review found twenty-seven works that exclusively obtain the results at a midpoint level (see Figure 1.18). A high level of uncertainty and lack of transparency of endpoint (or damage) categories is the common justification for using midpoint indicators (Dowdell, 2014; Ghose et al., 2017). Another possible explanation is the recommendation of the standard for environmental product declarations of construction products (EN 15804) and the standard for the assessment of the environmental performance of buildings (EN 15978), both requiring reporting midpoint impact indicators.

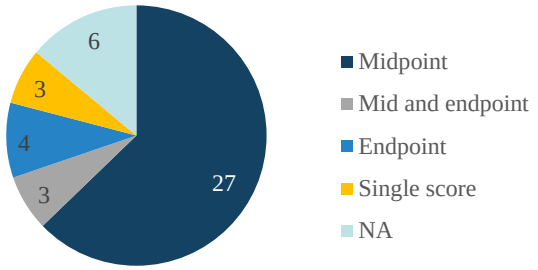

Figure 1.18 | Level of characterization factors

Three studies chose to analyze their results only through endpoint indicators (AzariJafari et al., 2019; Pedinotti-Castelle et al., 2019; Tanguay et al., 2021). The justification given by the authors is that even though being more uncertain, these indicators are easier to interpret and for decision-making (For more information about this debate, see (Bare et al., 2000)).

Three of the reviewed studies used a combination of both levels to analyze their results (Lesage et al., 2007a, 2007b; Roux et al., 2016; Taufiq Fauzi et al., 2021). According to Roux (2016) it is necessary to combine mid and endpoint levels because they do not provide the same information, complementing each other. Endpoint indicators are easier to interpret while midpoint indicators are more robust but more difficult to interpret.

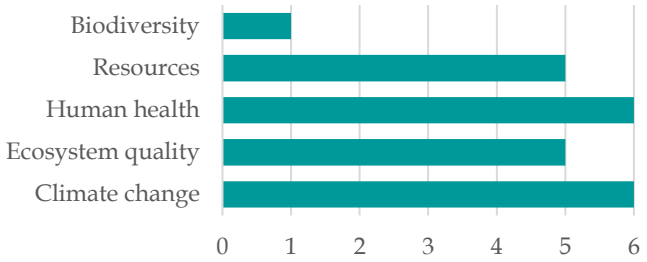

Figure 1.19 | Number of studies studying each endpoint indicator

All of the reviewed studies that assess midpoint and/or endpoint indicators, selected the global warming (or climate change) indicator. All studies that chose to present endpoint indicators, included human health damage, as presented in Figure 1.19. Biodiversity damage from Eco-Indicator 99 was only assessed by one study (Roux et al., 2016), as explained in (Roux, 2016).

As concerns the midpoint level, more than 40 indicators were presented by the reviewed studies. For practical reasons,

Figure 1.20 only presents the indicators that are employed in more than five studies. Eutrophication and abiotic resources depletion are the second most frequent indicators

presented in the reviewed studies. Abiotic depletion includes fossil fuels and mineral elements.

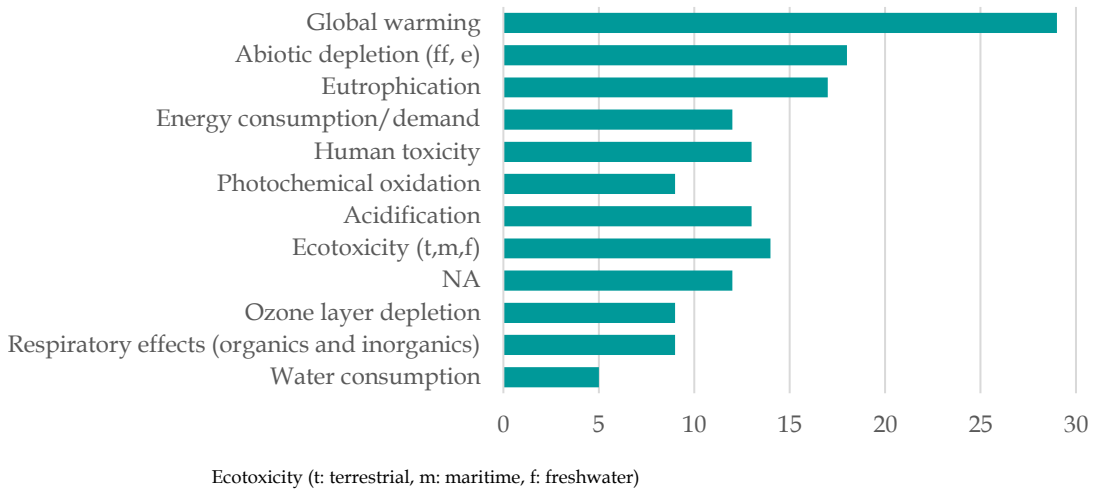

Figure 1.20 | Number of studies presenting the midpoint indicators

In addition, three studies chose to express their results as a single score (Buyle et al., 2019, 2018a, 2014). They obtained their results at midpoint and endpoint levels and also weighted them to obtain a single score. The justification is that a single score facilitates the interpretation and comparison of results.

1.4.7 Uncertainty and sensitivity analysis

Both stochastic (associated with variability of data) and epistemic (related to lack of knowledge) uncertainties influence LCA results and appear to be even more relevant for CLCA due to the assumptions for identifying the marginal suppliers (Brandão et al., 2014). Recently, Bamber et al. (2020) conducted a literature review on uncertainty sources and methods applied in both ALCA and CLCA. The authors found that more than half of CLCA studies at least mention conducting an uncertainty analysis while less than 35% of ALCA studies mention it. According to their review, the main sources of CLCA uncertainty are the economic data and behavior assumptions of economic modelling.

When conducting an LCA, it is recommended to carry out a sensitivity analysis for improving the reliability of the results. Sensitivity analysis is defined in ISO 14040/44 as "systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study". With regard to CLCA, the sensitivity analysis is particularly pertinent for giving a better understanding of the effects of the choices in economic relationships such as price elasticities and supply and demand equilibrium.

This reviewing criterion intends to describe whether and how these two issues are integrated into the CLCA studies.

Overall, sixteen studies do not mention uncertainty in their works (see Figure 1.21). Nine studies mention it, i.e., identify the main sources of uncertainty or include it as an important limitation of the study and propose it as a perspective for future work. As one would expect, the most cited source of uncertainty is associated with data availability and quality. Five studies mention that this is highly uncertain either because of the uncertainty related to trade partners or future prices. The long lifespan of construction systems is also mentioned as an important source of uncertainty, to identify the energy sources in the use phase or for affected technologies in end-of-life.

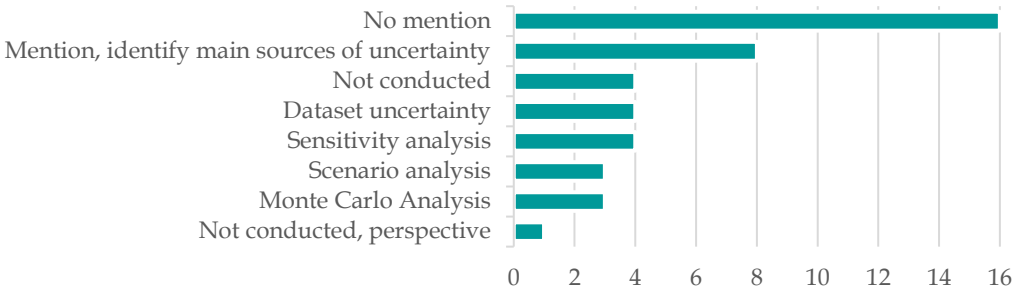

Figure 1.21 | Number of studies conducting uncertainty analysis

For the studies that conduct an uncertainty analysis, one of the following methods is used: Monte Carlo analysis (three), scenario modelling (three), dataset uncertainties (four), and sensitivity analysis (four). Monte Carlo analysis is applied by (AzariJafari et al., 2019) to propagate the uncertainties associated with three different sources: model uncertainty, data quality uncertainty, and variability. Roux et al., (2017) selected nine parameters including, for example, nuclear, wind power, and photovoltaic capacities.

This review found three studies that conducted a scenario analysis aiming at addressing the major uncertainties in CLCA. Buyle et al. (2019) proposed four scenarios in which a prospective or retrospective approach was combined with an iterative or network analysis procedure. (Prateep Na Talang et al., 2017) performed three consequential scenarios to study possible future technologies for producing fired bricks. (Sandin et al., 2014) studied four possible end-of-life scenarios for the glulam beam and two for the steel frame. The authors studied incineration and recycling varying the energy source in demolition and the marginal fuel for waste transportation in the future.

As mentioned in Section 1.4.3, twenty-one studies used a ScLCA combined with CLCA. All of them could be considered as using a scenario analysis for providing more robust results and reducing uncertainties, however only the ones that explicitly mention it as the purpose of conducting a scenario analysis are accounted for here.

The three studies that assessed the data uncertainties do not explain how they aggregate the uncertainties stated in by the different databases nor how they obtain the quantified uncertainties from the semi-quantitative methods (Pedigree matrix)(Kua, 2015, 2013b; Kua and Lu, 2016).

Even though sensitivity and uncertainty analysis do not have the same goal, a sensitivity analysis can be conducted on the most uncertain parameters in order to understand their influence on the results (Dodoo et al., 2014; Mathiesen et al., 2009). Dodoo et al. (2014) identified the main sources of uncertainty, such as building lifespan, building energy supplies, and transportation distances, and conducted a sensitivity analysis to obtain their implications on results. Kua and Maghimai (2017) used their sensitivity analysis to investigate any changes in the conclusions of their analyses resulting from data uncertainties.

Twelve other studies used a sensitivity analysis for assessing the variability of data in LCI, mainly in the production and/or use phase. The most common parameters analyzed are the transportation distances, assumptions on future suppliers, equipment efficiency and other use phase parameters, building lifespan, and time horizon of the change.

Three recent studies used a sensitivity analysis to verify the influence of the chosen LCIA method. All of them recalculated their results with the ReCiPe method (Huijbregts et al., 2016). While Taufiq Fauzi et al. (2021) found similar results in their sensitivity, Pedinotti-Castelle et al. (2019) found that human health impacts are higher with ReCiPe, because this latter includes global warming on human health, which contribute expressively to the impacts. Prateep Na Talang et al. (2017) does not provide any conclusions on the comparison of characterization methods.

1.4.8 Conclusions

Overall, the justification for choosing a consequential approach is associated with four different reasons: **to provide systemic information for decision-making**, to **expand system boundaries and also include substitution effects** (which is one of the methodological differences between attributional and consequential approaches), to **include indirect effects** and/or to **internalize environmental externalities**.

The authors that mention the pertinence of CLCA for helping decision-making mention the following examples of decisions: policymaking, to substitute or not a product or construction system, to compare circular building alternatives, to build or renovate a building, to buy or not a construction product, and to decide the future use of recovered brownfields.

Overall, half of the reviewed studies compare the results from both attributional and consequential approaches. The majority of the authors obtain significant differences in results, mainly justified by how the approaches deal with affected suppliers (marginal suppliers are more impacting) and avoided emissions (from substitution effects in CLCA approach).

In the reviewed studies, CLCA was combined with ScLCA, ILCA, MLCA, DyLCA, and PLCA[6]. The most common is to combine CLCA with ScLCA to deal with the lack of available information on consequential modelling, such as the affected suppliers. PLCA appears as the second most frequently combined approach to model the scenarios where future technological developments are compared to the business-as-usual ones. ILCA is also commonly combined with CLCA because the integration with other models, such as LCC, adds an economic layer that can be interesting to assess within CLCA.

Very few studies combined the CLCA with a sophisticated model (dynamic or not). **Only three studies are considered as MLCA**, of which two used a CEM and only two studies are considered as DyLCA because they used a dynamic LCI modelling.

Contrary to what would be expected from ILCD's guidelines, **the great majority of the studies assess a small-scale (marginal) change, proving the pertinence of CLCA independently from the scale of the change**. Only two reviewed studies can be considered as assessing a large-scale change. One of them used a CEM to identify the affected markets while the other one used market studies and literature with this purpose. It was found that it is common to mention the time horizon in the studies, the long-term consequences being the most frequent because these are the most dominating effects.

The methods for identifying the affected suppliers, which is the major challenge in CLCA, vary among the reviewed studies. The most frequent is the step-wise procedure from Weidema (2003, 2009), followed by trade-based methods, equilibrium models, and experts' opinions. The trade-based methods seem to be currently relevant in the literature and may help the construction sector to identify who is likely providing the demanded raw materials. The combination of these trade-based methods with consistent economic modelling is also an opportunity for the construction sector.

This review found that **rebound effects have seldom been studied by the construction sector under CLCA studies**. Though, this has been mentioned as a limitation and recommendation for future work in the most recent articles. Second-order effects from Sandén and Karlstrom (2007) were assessed by four studies when the increase in demand forces the supply side to adapt and respond to the demand. And, finally, the transformational effects from Greening et al. (2000) were assessed by a partial equilibrium model in one study. The integration of rebound effects remains very rare, and it seems to be an opportunity for future developments, since it may have a strong influence on the outcomes of the studies.

The use of midpoint indicators remains the most common among the reviewed studies. Examples of using single score and endpoint indicators are less common but represent ten studies out of forty-three. No particular impact category or indicator was mentioned to be

[6] ScLCA: Scenario-based LCA, ILCA: Integrated LCA, MLCA: Macro LCA, DyLCA: Dynamic LCA, PLCA: prospective LCA

particularly relevant for CLCA. The most common indicators among the reviewed studies are global warming and abiotic depletion

Uncertainty of CLCA is pointed out as one of its major limitations, however, **most studies do not conduct an uncertainty analysis**. The studies that include it use one of the following: Monte Carlo analysis, scenario modelling, dataset uncertainties, and sensitivity analysis. On the other hand, most of the reviewed studies conducted a sensitivity analysis, even if the main reason is not to assess the uncertainty of the studies, it seems to improve the robustness of CLCA results.

Even if mentioned as pertinent for policy-making, only one case study applied the consequential approach in this sense. Moreover, **it seems to be consensual that the consequential approach is also pertinent to include rebound effects and only seven studies included them in their assessments**.

Concluding, this review identified a few gaps. The first one is that, from our knowledge, very few studies have used consequential LCA for studying technological changes or new policies (large-scale changes). The second point is that there is no clear and unambiguous framework for including rebound effects of second or higher order as defined in Section 1.4.5. Finally, there is a lack of common ground to account for the uncertainty related to identifying the affected suppliers. The first two points are included in the research goals of the thesis, while the third point is left to future research, as it would depend on the development of the first two points.

1.5 Problem statement

The buildings and construction sector is part of the strategic approaches to achieve carbon neutrality in 2050, besides, the sector (through companies, institutions, associations) has engaged in specific initiatives and signed some agreements worldwide to reduce buildings emissions, wastes and energy consumption. The sector also has the perception that the stakeholders (clients, customers, investors, government, etc.) are increasingly demanding concrete actions so that the engagements and agreements will have a real effect. It means that the actions that are now applied in a unit of construction product, a unit of equipment, or a unit of building will need to be effective in higher extensions (large-scale decisions).

However, for now, the tools used by the buildings and construction sector to evaluate prove the environmental benefits of the proposed actions are mainly applied in small-scale decisions (units of construction product, units of equipment, and units of buildings). The question that appears evident is then "are these benefits in smaller-scale decisions still beneficial to the environment when they are propagated in larger extensions, where indirect effects could be significant?". And also, "whether and to what extension these actions contribute to the sustainable development goals?".

The hypothesis of the thesis is that the consequential approach is more appropriate for helping answer these questions since the upscaling from lower to higher applications may present cause-effect relationships that go beyond the product supply chain, and even more, beyond the normative system boundaries.

For this purpose, considering the difference in the concepts between ALCA and CLCA, and not based on the inaccurate perception that CLCA is only appropriate for large-scale decisions (Schaubroeck et al., 2021), the main objective of this thesis is to propose a methodological framework for carrying out a CLCA applied to large-scale decisions.

Research Questions

Considering the context presented above, mainly the lack of a consensual framework for assessing the environmental consequences of large-scale (major) changes occurring in the construction sector, the central research question proposed is the following:

RQ1: "How to assess the environmental consequences of major changes in the construction sector to help decision-making?"

The parallel research questions that this thesis will also answer are:

RQ2: What are the methodological needs for the application of consequential LCA approaches to the construction sector?

RQ3: How to model the propagation of the effects that are more evident for large-scale decisions?

2

Theories and methods – Background

Considering the construction sector's need for including an LCA perspective in decision-making, this chapter intends to provide the reader with a wider dimension of consequential LCA (CLCA) studies and how economic models can help these assessments. Accordingly, the chapter is organized as Figure 2.1 illustrates. Firstly, we review the use of CLCA for assessing large-scale decisions or policies, needing to explore sectors other than construction and buildings. Secondly, the review is focused on the methods associated with CLCA, providing their definitions, advantages and limitations for the purpose of the thesis. Finally, we provide the reader with the conclusions that lead us to develop the methodology of this thesis.

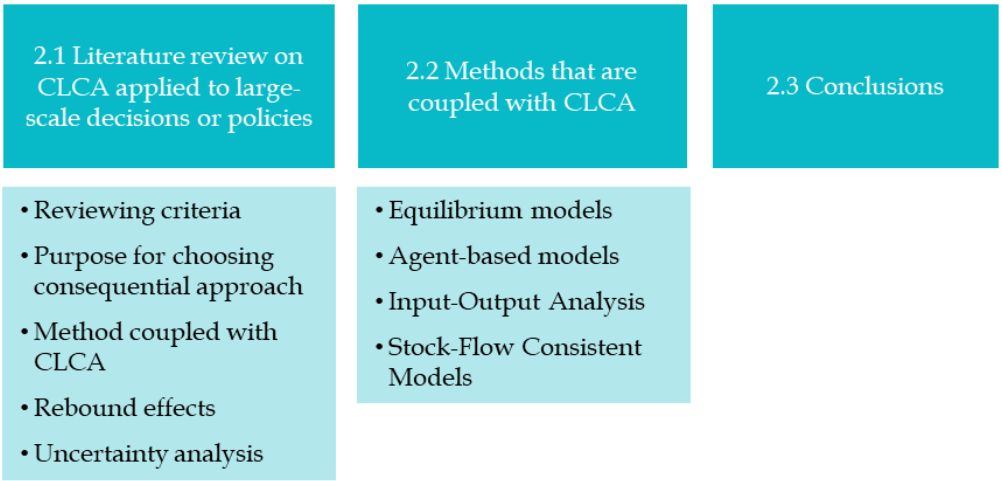

Figure 2.1 | Chapter 2 outline

2.1 Literature review on CLCA applied to large-scale decisions or policies

The research was conducted in July 2021 (and updated in January 2022) using current research tools, such as Scopus and Google Scholar. Scientific articles, theses and other studies in both English and French were included in this review. The search keywords were "consequential life cycle assessment" AND "large-scale" OR "policy" OR "technological change". The two works concerning "buildings" already analyzed in the previous chapter were not included in this review.

Forty-one studies were selected for further analysis. Thirty-four studies use a method for helping to identify the economic and social interactions occurring as a consequence of the studied change and apply the method into a case study. Four studies introduce only a methodological development, without presenting the results of a case study. Five studies are literature reviews on using economic models in CLCA, and one is a review of how rebound effects have been included in policy assessments.

The most recent reviews are from 2020. The one conducted by Luu et al. (2020) focus on the combination of economic and environmental models for developing a CLCA in the energy sector. The second one, conducted by Palazzo et al. (2020), is focused on the economic models used as the structure of CLCA, presenting the benefits and limitations of the reviewed models. Included in their review are the following models: economic equilibrium models, systems dynamics models, technology choice models, and agent-based models. The review conducted by Beaussier et al. (2019) focuses on the economic models used to support regional policies in the context of environmental assessments. The fourth review identifies and compares the methods that are available to assess the direct and indirect environmental impacts caused by the supply chain of traded agricultural products: life cycle assessment, environmental footprints and indicators, agent-based models, system dynamics models, equilibrium models and land use models (Paitan and Verburg, 2019). Lastly, the review carried out by Marvuglia et al. (2013) does not provide any numbers of recent applications of economic models; rather, the authors provide an overview of using simplified models and equilibrium models.

The selected reviewing criteria for this thesis are listed below:

- Fields
- Purpose
- Economic model
- Rebound effects
- Uncertainty

Fields

Table 2.1 presents the sectors that assessed environmental consequences of new policies or large-scale changes. Agriculture and biofuels represent the largest share of studies coupling an economic model with CLCA. One of the reasons for the particular interest of these sectors in the consequential approach is to understand the indirect land-use change (ILUC) effects.

Table 2.1 | Fields of the studies coupling an economic model with CLCA

Field	Number of studies
Energy	21
of which biofuels	*15*
Agriculture	8
Transportation	6
Circular economy	2
Policies in general	1
Non applicable	4

Transportation studies include the incentive policies for electric vehicles (Guo et al., 2021), mobility policies (Querini and Benetto, 2015), future transport scenarios (Albers et al., 2019; Somé et al., 2017) and the eco-design of cars (Whitefoot et al., 2011).

Concerning circular economy, even though being one the most trending topic nowadays (more than 700 search results in Scopus for "circular economy" and "LCA"), only two articles study subjects that are inscribed in this field. The most recent one proposes a methodological framework for studying the second life of materials and the second one studies the imports of combustible waste in district heating.

The studies considered "non-applicable" are two literature reviews that do not orient their research to a particular field listed here and two general methodological developments with no particular area of application.

2.1.1 Purpose for choosing the consequential approach

Contrarily to what was observed in the review results for the CLCA applied to construction sector (Section 1.4.1), the purpose for choosing the consequential approach the most cited among the selected documents is to include direct and indirect effects, as presented in Table 2.2.

Table 2.2 | Number of studies by purpose

Purpose	Number of studies
Direct and indirect effects	28
Prospective consequences	2
Not justified	7
Expand system boundaries	1
Include causal connections	1
Economic impacts	1
Market transformations	1

'Indirect effects' is a broad term and means different things for the reviewed authors. For example, eight of the papers explicitly state that the 'indirect effects' occur in other 'economic sectors', eight state that the 'indirect effects' are the 'induced effects' either resulting from the displacement, expansion, or intensification of the activities. Two studies define 'indirect effects' as the ones that occur beyond the supply chain, not necessarily in other economic sectors.

Other less common justifications for using CLCA include studying prospective consequences (Albers et al., 2019; Bichraoui-Draper et al., 2015), in accordance with the idea that CLCA is best adapted to anticipate future changes. Expanding system boundaries, which appeared as common justification in CLCA applied to the construction sector, was also cited by one study (Jones et al., 2017) in this current review. The authors justify their choice saying that CLCA can provide a broad environmental assessment, since "expanding study boundaries to include more impacts and use of marginal data, offer the potential to increase understanding of change within a system".

Another reason that was only mentioned once is that CLCA is able to assess the economic impacts, which often result in environmental consequences (Guo et al., 2021).

Finally, seven studies do not justify their choice of interest in CLCA, either because they are conducting a general review (one occurrence) or because they are assessing a change and CLCA is the most appropriate choice for that. This is the case of McDowall et al. (2018), for example, who state that CLCA models the possible consequences of adding or removing additional units of a technology to a system.

2.1.2 Method coupled with CLCA

As mentioned in Section 2.1, five of the selected documents are literature reviews with similar purposes as this current review. The most recent one presented by Luu et al. (2020) found forty-three papers that applied at least one economic model to quantify the indirect environmental changes. According to the authors, the most frequently applied models are Partial Equilibrium (PE) model, Computable General Equilibrium (CGE) model, Agent-Based Modelling (ABM) and System Dynamics (SD). A review on these models is presented in Section 2.2, p. 57.

The second most recent one is from Palazzo et al. (2020), which reviews equilibrium models, system dynamic models, technology choice models and agent-based models. The authors provide a detailed analysis of each one of these models and some applications to CLCA studies. Equilibrium models represent the largest amount of studies when compared to other models.

The third review, provided by Beaussier et al. (2019) showed that, overall, PE and CGE coupled with environmental footprints or LCA are the most applied today. However,

couplings involving a third tool can be beneficial, such as ABM or MFA, since they may allow overcoming some shortcomings such as agent behavior modelling or data availability for biophysical flow.

Lastly, Marvuglia et al. (2013) presented the benefits and limitations of some models that are coupled with LCA for biofuel and conclude with a proposition of framework for consequential assessment of biogas production. The authors suggest starting the assessment with a simplified model that can identify major affected markets, which will lead to decide between using CGE or PE (or a combination of both).

The results of this thesis review are in accordance with the previous findings. As presented in Figure 2.2, the majority of the studies present an equilibrium model to identify and quantify the market effects. The most frequent is the use of a PE, which can be justified by the fact that it is relatively simple to combine LCA with PE (Luu et al., 2020). The first application found in the review was conducted by Whitefoot et al. (2011). In this study, the methodology is applied to a design decision to downsize the engine of a mid-size vehicle by 25% and conclude that the proposed methodology captures important ripple effects that could influence decision-making.

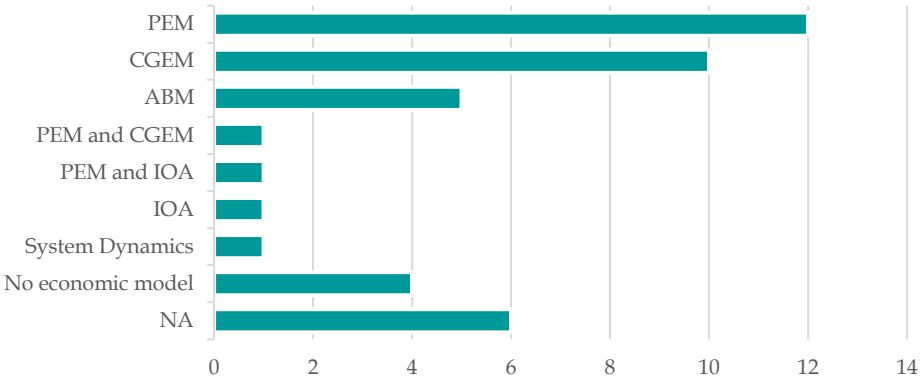

Figure 2.2 | Use of economic models in CLCA

CGE, the second most applied economic model, is used in ten publications, of which, eight chose the model from the Global Trade Analysis Project (GTAP). GTAP is a global consortium composed of researchers and policy makers, coordinated by the Purdue University, for quantifying international policy issues (GTAP, 2022). Dandres (2012) was one of the precursors of coupling GTAP with CLCA (MCLA as presented in Table 1.1 for studying the global effects of environmental policies due to the considerable level of disaggregation of economic sectors in the model (Dandres, 2012).

The third model that appears in Figure 2.2 is ABM. The first reviewed ABM-LCA study dates from 2013 and was conducted by Miller et al. (2013). It studies the emerging use of switchgrass to produce biofuels in order to meet renewable energy goals. ABM is chosen to include the landowners' behavior through three attributes: profitability, resistance to change, and technology familiarity. In 2015, Bichraoui-Draper et al. (2015) followed the paths of Miller

et al. (2013) and studied the deployment of switchgrass-based biofuels; however, they included a dynamic layer to anticipated environmental changes in the agricultural system relative to the baseline condition.

Some authors have coupled ABM to CLCA to study mobility systems (Querini and Benetto, 2015, 2014). The choice of ABM is justified by the importance of driver behavior and social interactions in mobility policies.

The most recent ABM-CLCA works found in this review are related to agriculture processes (Marvuglia et al., 2016; Navarrete Gutiérrez et al., 2017) and are a part of the project *MUlti agent Simulation for consequential life cycle assessment of Agro-systems* project (MUSA), developed by the Luxembourg Institute of Science and Technology (LIST).

Navarrete-Gutiérrez et al. (2017) and Marvuglia et al. (2016) introduced the agent behavior as adding a "green consciousness" component in farmers' decisions, substituting a rational approach based on profit maximization (common in equilibrium models).

One study coupled a PE and IOA with CLCA for understanding the materiality of indirect emissions of the implementation of low-carbon technologies in Europe (McDowall et al., 2018). According to the authors, input-output table can be disaggregated to better represent the techno-economic characteristics of energy systems using the detailed information that is provided by the TIMES model (acronym for The Integrated MARKAL-EFOM System), which is a partial equilibrium economic model.

Katelhön et al. (2016) used an input-output model called Rectangular Choice-of-Technology (RCOT), which is a type of technology choice model. In this model, more than one technology can produce one product, so they used it to study the choice between irrigation technologies for agricultural production and also the choice between bio- and petroleum-based fuels.

The only reviewed study coupling a SD with CLCA is provided by Correa Hackenhaar et al.(2022). The authors used an SD to simulate the behavior of non-linear systems, where a large number of elements interact over time. The feedback loops occur between the market for the product and the supply and demand dynamics.

The six studies that are considered as 'non-applicable' are the literature reviews. Finally, four studies do not use an economic model. Andreasi Bassi et al. (2021) studied the increase in recycled content of polyethylene terephthalate trays. The authors proposed a set of equations for obtaining the mass balances of a large-scale adoption of this practice. Besides, no LCIA was conducted. The second study not using an economic model was provided by Jones et al. (2017), which used BLCA to study the cause-effects relationships of increasing the renewable energy supplying the electricity grid. The authors used the net energy analysis (NEA) to obtain the energy return on energy investment (EROI), defined as the ratio of the gross energy output to the sum total of energy investments, and help to identify the marginal data.

The two remaining studies are provided by Styles et al. (2015a,b), which used the tool called LCAD developed by the authors based on the information collected from a technical working group. The LCAD tool was commissioned by the UK government's department of agriculture and the environment to compare the environmental performance of on-farm anaerobic digestion of wastes and farm bioenergy options.

2.1.3 Rebound effects

It was observed in the previously conducted literature review that socio-economic models are integrated with CLCA for assessing economy-wide rebound effects (Dandres, 2012; Ekvall, 2002). As explained in Section 1.4.5, rebound effects terminology is not consensual in the literature. This reviewing criterion has the purpose of identifying whether the methods applied in the studies assess the rebound effects (following or not the typology described in Table 1.4) and when it is the case, what types of effects are included and how they are modelled. The results concerning the types of rebound effects are presented in the Figure 2.3.

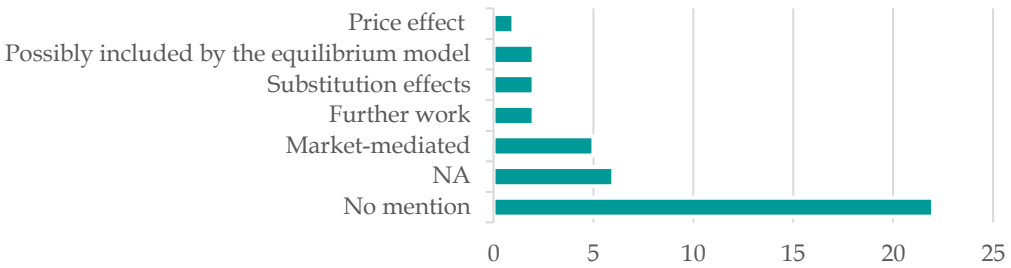

Figure 2.3 | Rebound effects assessed by the reviewed studies

More than half of the articles do not mention rebound effects in their studies; two studies which do not include these effects, say, however, that they should or will be included in future work. In two studies that couple an equilibrium model to CLCA, the authors explicitly say that the equilibrium models probably include the rebound effects; however, they do not specify their understanding of which rebound effects could be included in the models.

Overall, among the forty reviewed studies, only eight explicitly include rebound effects in their assessments. Four of them include market-mediated effects, defined by Andreasi Bassi et al. (2021) as the effects resulting from the reduced demand for primary material leading to increased consumption of other goods using that material. This is the case observed by Dandres et al. (2011, 2012), where the reduction of supply prices increased the coal and lignite production in Europe, increasing their availability for export and for local consumption. The same type of rebound effect was observed by Rajagopal et al. (2011), where domestic biofuel policies reduced oil demand, decreasing the world oil price and increasing consumption elsewhere.

Plevin (2017) also includes market-mediated effects, however, the definition applied in his work is broader than the one provided by Andreasi Bassi et al. (2021), as follows: "market-mediated describe changes in production and consumption triggered by changes in prices, efficiency and technology". For Plevin (2017), the definition of Andreasi Bassi (2021) is considered as price effects on supply and demand. Also according to the author, income effects occur when a consumer spends more (or less) for a good and then has less (or more) residual income to spend elsewhere. Spillover effects occur when improvements in one technology enable improvements in other technologies or activities.

Two studies assessed substitution rebound effects. For Deepak Rajagopal (2014), these effects are evaluated by the elasticity of supply of the substitutes; for example, if the ethanol mandate lowers the price of the ethanol-gasoline blend, then the more inelastic the demand for fuel, the smaller the rebound in gasoline consumption will be. Guo et al. (2021) studied the elasticity of the substitution between the internal combustion engines and electric vehicles represented by different scenarios of technological progress and subsidies modelled in CGE.

The studies that appear as non-applicable are the six reviews, even though one of them, as mentioned in Section 2.1, focuses on studying how rebound effects can be included in resource efficiency policies in three sectors, namely buildings, energy services and mobility, and food (Vivanco et al., 2018). The latter provided some conclusions with regard to the relative importance of rebound effects on the overall impacts of new policies. According to the authors, energy rebounds are fairly exploited in the literature for the three sectors, while water and land use rebound effects have only been studied in food policies. They point out the need to include rebound effects in reaching SDGs as interlinked activities and linkages between individual goals are affected (and more, can be stimulated) by rebound effects.

When comparing these results with those obtained in the literature review of CLCA applied to the construction sector (Section 1.4.5), the proportion of studies evaluating a rebound effect is almost two times higher here. The common perception that large-scale changes might present relevant rebound effects justifies this difference in results.

2.1.4 Uncertainty

As introduced in Section 1.4.7, a higher level of uncertainty is often associated with CLCA, being cited as one of the major limitations of this approach. According to (Plevin, 2017), when introducing the cause-effect relationships, the CLCA is more accurate, but less precise. This perception is associated with three main reasons: greater number of assumptions when compared to ALCA, the indirect effects that are included and the elasticity of system boundaries (Vázquez-Rowe et al., 2014a; Zamagni et al., 2012). The purpose of including this reviewing criterion is to understand how the economic models quantify uncertainty.

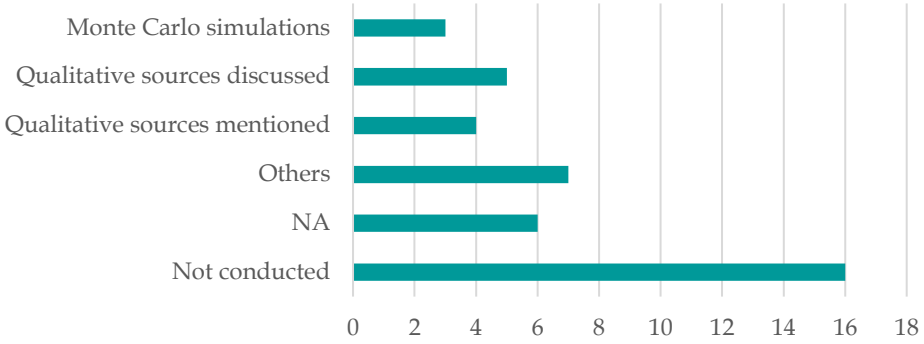

Figure 2.4 | Number of CLCA studies conducting uncertainty analysis

Overall, Figure 2.4 shows that most of the reviewed studies do not conduct any quantitative or qualitative uncertainty analysis, not mentioning it as a possible limitation. In nine studies, qualitative sources of uncertainty are identified, five of which present a discussion on this matter, which are detailed hereafter.

Vazquez-Rowe et al. (2017), for example, discussed the level of uncertainty associated with the PE model. According to the authors, the use of the PE model reduce the uncertainty associated with the elasticity of the system boundaries, and also the many assumptions that are done without an economic model. The authors also distinguish between two types of uncertainty associated with the market, the first is internal and regards the positive and/or negative feedback, and the second is external and may go from the changes in price elasticities to changes in the agriculture trade worldwide.

Nguyen et al. (2013) discussed the uncertainty associated with 'land use change' impact from switching from maze to grass for animal feed. According to authors, the main source of uncertainty is related to GTAP, the CGE model, which use a set of parameters and assumptions often with high uncertainty. The emission factors are also cited as a possible source of uncertainty in general, the authors use the ones from IPCC 2006, which have relatively high uncertainty. To conclude, the authors recommend the use of scenario analysis to overcome the uncertainties associated with the cause-effect pathways, to integrate other possible consequences of switching from one system to another.

According to Vázquez-Rowe et al. (2013), in general, PE models do not represent the market interactions in a consistent way, providing a restricted representation of reality. This can be, according to authors, one of the major sources of uncertainty of CLCA coupled with PE. For this reason, the authors proposed three scenarios. In the first, the farmer's revenue is maximized and some parameters related to crop growth are endogenized. Also in this scenario, the regulatory constraint concerning the limit of annual crop rotation is taken into account. The second scenario minimizes the opportunity cost; the main changes occur

exogenously and no optimization is foreseen. The third scenario is based on expert's opinion and present the higher level of uncertainty, according to the authors.

Dandres et al. (2011) pointed out the uncertainties associated with combining the data from different sources. The authors' intention to use input-output tables (IOT) from the statistical reporting authorities from different countries would not be consistent and increase the level of uncertainty. For this reason, even considering that IOT would fit correctly with their purpose, they chose to use the Ecoinvent database and combine it with other databases and tools.

Finally, Kløverpris et al. (2010) described the main sources of uncertainty associated with the GTAP model, all of them considered as presenting low uncertainty by the authors. Firstly, the authors mention the land availability presented in GTAP, which may present possible overlaps between the areas. The second consideration is the year when the database was created, having a delay of almost one decade from the study. According to the authors, the uncertainties associated with it are considered low because the main aspects were updated in the recent versions of the model. They also mention the combination of two different data sources to obtain the crop yields as a possible source of uncertainty. The final issue is the identification of the biome areas affected by the crop development within regions.

Three studies run Monte Carlo simulations to propagate uncertainties, the case of Dandres et al. (2012), Igos et al. (2015) and Katelhön et al. (2016). Concerning other methods, one used conventional sensitivity analysis, one used a global sensitivity analysis, three used scenario analysis, one used confidence intervals and one based its analysis on Bayes's theorem.

2.1.5 Conclusions

Forty articles using CLCA to study policies or non-marginal changes were reviewed. The fields that appeared more frequently in the results are **agriculture and biofuels**; one possible reason for their particular interest in the consequential approach is to understand the indirect land-use change (ILUC) effects.

In line with this hypothesis, the majority of the studies justify the choice for using a consequential approach to assess the **direct and indirect impacts**. The latter means **'going beyond supply chain activities'** for some authors, **'effects on the other sectors'** for other authors, or even still **'induced effects'**.

Overall, the economic models that are more frequently coupled with LCA are the **equilibrium models (PE or CGE)**, **agent-based model (ABM)**, **input-output analysis (IOA)** and **system dynamics**.

More than half of the articles do not mention rebound effects in their studies, only one fifth explicitly including them in their assessments. **Market-mediated effects**, specifically

price effects on supply and demand, are the most cited by the authors. Two studies assessed substitution rebound effects, evaluated by the elasticity of supply of the substitutes, which can be directly obtained from the equilibrium model used in both studies.

Finally, and **the most recurring, is to not include a thorough uncertainty analysis**. Even though, three projects studied the uncertainties through Monte Carlo simulations and two used sensitivity analysis, of which one used a global sensitivity analysis.

2.2 Models that are coupled with CLCA: definitions, advantages and limitations

The most frequent models coupled with CLCA in the literature, according to our review and the previous reviews, are the equilibrium models (PE or CGE), followed by agent-based modelling (ABM) and input-output analysis (IOA). This section presents the definitions, advantages and limitations of these three (socio)-economic models and also clarifies in what measure they are able to include rebound effects. These factors combined will help to answer the research questions 2 and 3, presented as a reminder in Box 1.

Box 1

RQ2: What are the methodological needs for the application of consequential LCA approaches to the construction sector?

RQ3: How to model the propagation of the effects that are more evident for large-scale decisions?

Before going deeper into the models, it is important to clarify some points. RQ2 is interested in pinpointing the methodological needs for applying a consequential approach, i.e., the methodological needs to identify the activities that "are expected to change as a consequence of a change in demand for functional unit", according to UNEP (2011) definition. RQ3 is focused on the propagation of the effects, also known as rebound effects. Therefore, it is worth analyzing the ability of the reviewed methods to identify and propagate the activities that change in function of an extra unit of the functional unit, and to what extent (or in what degree, or order).

Rebound effect is a broad term and needs to be defined for clarification. In this thesis, we distinguish "first-order" from "second-order" effects as follows. The term "first-order effects" corresponds to the activities that occur as a result of a specific expenditure (consumption decision) until it has overflowed from these activities in the form of payments for primary factors (wages, production taxes, entrepreneurial income, and rents). This includes activities that occur as rebound effects of consumer price differences since these activities also occur as a result of a specific consumption decision.

The term "second-order effects" is then defined as the effects of a specific spending decision on income redistribution and/or productivity growth. These effects occur after the original expenditure has been received by the primary factor agents (laborers, government or recipients of tax redistributions, entrepreneurs, or rentiers), i.e., as a result of re-spending the original amount in subsequent spending loops.

Income redistribution is the mechanism that describes how the money received by primary factor agents is ultimately redistributed among agents involved in all economic sectors and income classes. To understand this mechanism, information about savings, investments, and profits is needed. In addition, as productivity is affected by investments, income redistribution has an important effect on productivity growth, as well as the parameters and equations that are used to quantify consumer behavior, such as propensities to save and consume, consumption patterns, and consumption and production functions.

Productivity growth occurs when innovation takes place within a firm (microeconomic phenomena) and, as the innovation is adopted by other firms, it has consequences for other economic activities (macroeconomic consequences). Numerous sophisticated economic models studying these effects, from different economic schools (neoclassical to heterodox) can be found in the literature (for reviews, see Blecker and Stefford, 2019 and Kemp-Benedict, 2017).

Therefore, the review on the four models is based on the following key aspects:

- Level of transparency
- Data collection
- Ability to include rebound effects (first and second order)
- Ability to include trade flows
- Ability to include financial flows

The level of transparency is important to understand the mechanisms behind the model and the equations representing the hypothesis of the model. A high level of transparency allows justifying the results and also applying or proposing improvements for a better representation of the studied system.

Data collection is included as a decisive criterion for selecting a method as collecting data for modelling can be very time consuming and it is one major challenges in research. Other issues related to the existence of databases that can be used by the models are also important, as regular updates, representation level of technologies, disaggregation of data, and others. As these other criteria are more related to the database than to the method, they were left outside the scope of the review.

The ability of the model to include rebound effects is studied mainly because of the research question RQ3, as mentioned in the beginning of this section. In a globalized world, the economic activities are interlinked going beyond the territorial borders and displacement

of impacts is one of the issues often identified in the previous researches. For these reasons, how the model deal with trade flows is analyzed as one criterion.

Finally, we live in a highly financialized economy extremely interconnected. Financial capital is not restricted to border limitations and any policy or technological change has a role on the matter of the changes in stocks (balance sheets). This criterion was included to understand the capability of the model to capture the financial side of the economy.

2.2.1 Computable Equilibrium Models

Equilibrium models simulate the new market equilibrium after a perturbation, based on two pillars: consumer utility maximization and producer profit maximization (Yang & Heijungs, 2018). The long-term equilibrium is obtained using a system of equations that describe producer and consumer behavior (production and utility functions), controlled by market-clearing constraints. The parameters used in these equations are obtained from a calibration of the model, where an initial equilibrium is calculated using a Social Account Matrix (SAM), the production and utility functions, and the elasticity parameters. The choice of the endogenous and exogenous parameters is done at the closure phase when it's decided what is fixed and what is variable to attain the equilibrium (Burfisher, 2012).

In these models, the second-order effects are assessed through the so-called multiplier effects, which involve circular flows of income within the economy resulting from the injection of additional spending. Multiplier effects are obtained by the production and consumption linkages from the SAM, also known as SAM multipliers, which trace the links between changes in demand and changes in production, household income and final demand (Breisinger et al., 2009; Robinson, 2006; Thorbecke, 2000).

Being SAM-based models, equilibrium models include these linkages and also add other factors to the equations used to determine the equilibrium. An example is making prices exogenous so that an exogenous shock will establish a new set of prices, which will consequently define the new production, consumption, employment and incomes (Thorbecke, 2000). Two types of computable equilibrium models appeared in the review and are suitable to coupling with CLCA: partial and general.

► Partial Equilibrium models

PE theory was developed by the English economist Alfred Marshall and, later, detailed by the French economist Antoine Augustin Cournot (Shobande et al., 2021). Partial equilibrium is defined by the Cambridge dictionary as "a balance between supply and demand in just one part of an economy" (Cambridge Dictionary, 2022).

PE models estimate the impact of a change in the economy, not requiring the complete solution of new general equilibrium (Whalley, 1975). PE theory is based on the ceteris paribus assumptions, i.e., the income and prices in the rest of the economy stay fixed (Burfisher, 2012).

The main advantages of these models are their simplicity when compared to CGE. These models have minimal data requirements, since it only requires trade flows, trade policy, and elasticities; flexibility in relation to aggregation/disaggregation, allowing the analysis in a disaggregated level compatible with process-oriented inventories; and transparency, meaning no 'black box' as it happens for CGE (World Bank, 2010).

On the other hand, the limitations that appear are the limited number of economic variables that are included; due to its simplicity, it may lack important feedback between various markets creating a high level of uncertainty when predicting future elasticities (World Bank, 2010).

► Computable General Equilibrium models

CGE models are a system of equations that describe an economy as a whole and the interactions among its parts. CGE are "computable" because of their capability of quantifying the effects: "general" because they involve several optimizer agents, and "equilibrium" because the prices are determined by supply and demand (United Nations, 2017).

Particularly to CGE, the closure phase imposes that total savings equals total investments and thus the choice of whether the first or the second one is exogenous or endogenous will have a different result in the calculations of changes in economic flows (Burfisher, 2012). For example, the GTAP model is a 'savings-driven' model since it assumes that savings rates are exogenous and constant so that the investments must adjust to the changes in savings. More specifically, the savings change proportionally with the income, and the investments are adjusted to fit those changes, affecting, for example, industrialproduction (e.g. through the capital investment) (Burfisher, 2012).

CGE models present an advantage relative to PE models because they characterize a broader system. The availability of data and the existing well-established models (built by research consortiums) also appear as advantages of using CGE.

CGE (and also PE) models are often criticized by misrepresenting reality (Caiani et al., 2016; Querini and Benetto, 2015). The CGE limitations are largely discussed in the literature; the reasons that commonly appear are the assumptions of perfect behavior, as, for example, hyper-rationality of individuals, which implies that the agents know the "true model" of the economy and will react rationally to a shock (Gaffard and Napoletano, 2012; Godley and Lavoie, 2007). The assumption of equilibrium, with market-clearing mechanisms, neglecting that some goods may be unsold and there might be fluctuations of inventories is also often a point criticized in the literature (Gaffard and Napoletano, 2012; Godley and Lavoie, 2007; Robinson, 2006). Finally, the most important limitation regards the misrepresentation of the financial institutions within the economy. Banks are often overlooked and their role is not represented as an important feature of these models.

2.2.2 Agent-Based Models

ABM are bottom-up, non-linear and dynamic socio-economic models that take into account the interaction between the different agents involved in the study. Agents are completely autonomous and make decisions according to a set of rules in common to all entities that are regrouped as the same agent (Bonabeau, 2002; Davis et al., 2009; Querini and Benetto, 2014).

The studies coupling an ABM with an LCA are generally applied to assess the environmental impacts associated with a policy implementation or to emerging technologies (for a review, see Micolier et al., 2019) and some of them use a consequential approach (for example, Lu & Hsu, 2017; Marvuglia et al., 2016; Miller et al., 2013; Navarrete Gutiérrez et al., 2017; Querini & Benetto, 2014; Vázquez-Rowe et al., 2014). In these studies, the heterogeneity of individuals is a central feature, so that their behavior, including their propensity to adopt change, and production/consumption preferences can be modeled and included in the simulations (Gaffard & Napoletano, 2012).

One of the greatest advantages of ABMs is that they can adapt considerably depending on the purpose of the model ABM. For example, it can include technological changes and productivity growth, by integrating socio-economic data at a micro-economic level (investment functions). Even if some types of ABMs are also able to include monetary redistribution (Gaffard and Napoletano, 2012), no example of this application was found by our research.

On the other hand, ABM are very complex to model and data collection can be very difficult and time consuming (Luu et al., 2020). Another disadvantage that appears in the literature is the lack of transparency in behavior modelling (Palazzo et al., 2020).

2.2.3 Input-Output Models

Input-Output (IO) model is a macro-economic modelling approach in which the different economic sectors or industries are linked by their economic interrelationships (physical or monetary) through the input-output tables (IOT). The theory of IOA was developed by Wassily Leontief (Leontief, 1936), who won a Nobel prize for his work. Combining the IOA with LCA is a common practice, also known as Hybrid-LCA (HLCA), when the IOT has an environmental extension (EE-IO). The mathematical framework of this particular type of coupling is well described in the Chapter 5 of the book "The Computational Structure of Life Cycle Assessment" from Heijungs & Suh (2003).

Input-output tables are built from supply-use tables (SUT), the methodology for doing so is properly explained in the economic literature. A recent reference describing the transformation of SUTs into IOTs is the *Handbook on Supply and Use Tables and Input Output-Tables with Extensions and Applications* (UN, 2018), precisely the Chapter 12. Supply and Use

tables describe the supply and use of products (rows) by industries (columns). Therefore, there are two main possible ways for transforming a SUT into an IOT, either compiling them in a product-by-product system or in an industry-by-industry system.

When combining IOA with LCA, it is recommended to use "product-by-product" IOTs, because the most logical way of identifying the unit processes defined in LCA follows the product-by-product system (Majeau-Bettez et al., 2014).

Majeau-Bettez et al. (2018) provide an extensive analysis on six procedures (models) for dealing with multi-functionality when constructing a product-by-product IOTs. Tha authors also analyse how these constructs are consistent (or not) with attributional and consequential modelling. The six models evaluated by the authors are sub-division, system expansion, partitioning allocation, alternate-activity allocation (commodity technology construct and alternate activity construct), substitution (by-product technology construct) and lump-sum.

The partitioning allocation occurs when the requirements of an activity are split across the different outputs based on a common property of the products (Majeau-Bettez et al., 2014), which is perfectly compatible with the attributional approach (Majeau-Bettez et al., 2018).

The consequential modelling is compatible with the commodity technology construct (CTC) and the by-product technology construct (BTC). The CTC isolates a unique input structure of a primary product from the other outputs (co-products) by subtracting the processes in which the co-products are produced as a single product. The key assumption in the CTC is that it is possible to separate the inputs and outputs of a single product from the ones of the co-products by substracting similar independent production of the co-products (Suh et al., 2010). The BTC assumes that the co-products substitute equivalent products produced produced as a single product in other processes, being equivalent to the substitution (see Figure 1.9).

The other constructs may also be compatible with attributional and consequential modelling, nevertheless violating some principle of the modelling approach (Majeau-Bettez et al., 2018).

The first order effects are directly obtained from expanding IOT, as described in (Weidema et al., 2018). To the extent of our knowledge, second-order effects have not been assessed through IOA. In conventional IO models the potential technology learning curves, or the idea that the inputs and factors of a given technology may not scale linearly with activity levels (Palazzo et al., 2020).

The greatest advantage of using IOA is the data availability and the well-established methodological framework for coupling with LCA. However, there is no link with the financial side, since no stock is represented in the analysis in conventional IOT.

Table 2.3 presents a summary of the identified advantages and limitations of the four economic models reviewed in this chapter.

Table 2.3 | Comparison between the reviewed models

	Equilibrium models		Agent-based models	Input-Output models
	PE	CGE		
Advantages	• Simplicity when compared to CGEM • Minimal data requirements, only needs: trade flows, trade policy and elasticities • Allows the analysis in a disaggregated level • Transparency (no black box)	• Characterize a broader system • Availability of data • Well-established models	• Adaptable to include technological changes and productivity growth	• Data availability • Capability to couple/relate with LCA • By-product technology and commodity technology are consistent with consequential modelling
Limitations	• Limited number of economic variables • Due to the simplicity, it may miss important feedbacks between various markets • Prediction of future elasticities may have important uncertainties	• Black box effect • Uncertainties of market reactions	• Difficulty to collect data • Complex to model	• High-aggregation level • No finance in the modelling
	Limitations of both PE and CGE: • Financial side is misrepresented (banks often neglected) • Assumption of equilibrium, with market-clearing mechanisms (maximizing profit and optimizing utility functions), neglecting that some goods may be unsold and there might be fluctuations of inventories • Perfect behaviour (no ability to change behaviour)			

2.2.4 Stock–Flow Consistent models

Considering the limitations presented in Table 2.3, new research was conducted to find other economic models that could address the identified gaps, mainly the ones related to providing a better representation of the financial side of the economy. On this matter, knowing that the latter was a recognized issue among the macroeconomists (Godley and Lavoie, 2007), stock-flow consistent models (SFC) were developed with this purpose.

SFC models are mostly inspired by the post-Keynesian school (Kaldor and Kalecki) and the Keynesian Yale school, following one of the major contributions of Keynes concerning the importance of combining real and monetary sides of the economy (Godley and Lavoie, 2007). Another economist that inspired SFC models is Hyman Minsky, mainly for his contributions with regard to banking behavior (Le Héron, 2018).

Therefore, SFC theory proposes an integration between the financial and the income accounting, based on the idea that the economy is demand-driven, even in the long-run (Zezza and Zezza, 2019), and that the disequilibria in the short-term causes adjustments (Godley and Lavoie, 2007).

These models have gained particular visibility over the past 10 years, especially because they were more accurate than other models in predicting the economic and financial crisis of 2008. They respond in particular to three main principles (Nikiforos and Zezza, 2017):

- The consistency of the flows, in which the income of someone is a payment coming from someone else, so that there are no "black holes"
- The consistency of stocks, in order to respect the accounting rule according to which the assets of one sector are the liabilities of another, and net financial wealth for all sectors is zero
- The stock-flow link, explained by the fact that flows imply a change in stock

When these principles are combined, the result is what is called as the quadruple-entry principle in a transaction flow matrix (TFM). This principle was firstly introduced by Morris Copeland, and means that each of the columns and each of the rows must sum to zero at all times, it follows that any alteration in one cell of the matrix must imply a modification to at least three other cells.

Godley and Lavoie (2007) present in their book the main features for building an SFC model. In their work, they provide pedagogical models and discuss the equations from simplified to more sophisticated and complex economies.

2.3 Conclusions and selected methods from the literature review

Table 2.4 presents the results of the review on the methods coupled with LCA for helping identifying the social and economic interactions that occur as a consequence of the studied change. In the table, the SFC models are added as all methods currently existing in the CLCA literature do not include the financial side of the economy (see Table 2.3).

Table 2.4 | Comparison of the reviewed models based on five criteria

Criteria	**Equilibrium models**		**Agent-based models**	**Input-output models**	**Stock-flow consistent models**
	PE	CGE			
Level of transparency	High	Low (black box effect)	High	High	High
Data collection	Several databases are available	Several databases are available	Complex to gather data, depending on the level of disaggregation of agents	Several databases are available	Multiple databases are needed, from different sources, relatively complex to gather information
Ability to include rebound effects	Able to include both first and second-order effects, however, only partially as it covers only a part of the economy	Able to include both first and second-order effects	Able to include both first and second-order effects	Normally only first-order effects	Able to include both first and second-order effects
Trade flows	Normally included, may be partial	Normally included	Normally not included, only when coupled with an economic model	Included in multi-regional IOT	May be included when needed to be modelled
Financial flows	Often neglected or very simplified	Often neglected or very simplified	Normally not included, only when coupled with an economic model	Not captured	Good representation of the financial side of the economy

Why use an economic model, and which model to choose?

Resuming the research questions motivating this chapter, the first goal was to identify the methodological needs for the application of consequential LCA approaches to the construction sector. The second goal was to identify the methods that are used to propagate the effects that are more evident for large-scale decisions.

The literature review on using CLCA as a methodology to assess large-scale decisions or policies showed that economic models can be very useful for helping to identify the activities in the product system that are expected to change as a consequence of a change in demand for functional unit. The simple models, as presented in (Weidema et al., 2009), can be very helpful in identifying major affected markets, however, when there are other indirect effects, the market-mediated rebound effects as defined by Plevin (2017), an economic model based on multi-regional database is needed.

First-order effects are fairly well-described in the literature; for example, the use of consumer-oriented approaches such as applying Engel curves (Font Vivanco et al., 2015), marginal propensities to spend (Alfredsson, 2004), marginal income changes affecting the consumption patterns (Thiesen et al., 2008) or the use of industry-oriented approaches, such as the use of marginal production cost (Kätelhön et al., 2015).

Within the field of environmental assessments, particularly in life cycle assessments, as described in the previous sections, productivity growth has been studied by integrating agent-based models (ABM) and learning curves or power law relationships. In addition, we also found examples of including income redistribution effects by using computable equilibrium models, which are also able to consider productivity growth effects.

Learning curves and power law relationships show how cumulative production experience and average costs are associated, allowing the consideration of scale (Argote and Epple, 1990; Bergesen and Suh, 2016). Being simple and intuitive tools, these two are not intrinsically associated with investments and other monetary relationships between different economic sectors, but they could be integrated in economic models. Examples of using learning curves to assess productivity growth can be found in Bergesen and Suh (2016) and Sandén and Karlström (2007).

Computable equilibrium models, PE or CGE, are able to cover productivity growth through the price equilibrium equations indexing each firm by its productivity, taking into consideration the respective (expected) growth rate.

Income redistribution may be assessed by CPE and/or CGE through the multiplier effects, resulting from the perturbation of the circular flow of income within the economy by the injection of additional spending. Multiplier effects are obtained from the production and consumption linkages from the Social Accounting Matrix (SAM), also known as SAM multipliers, which trace the effects of changes in demand through changes in production,

household's income, and back to final demand (Breisinger et al., 2009; Robinson, 2006; Thorbecke, 2000).

Even though closely related, the income redistribution effect can be analysed separately from its possible influence on productivity growth. In this thesis, we limit ourselves to the effects of income redistribution, and leave the productivity (growth) puzzle to future research. Considering the relevant limitations of CGE models when it comes to the representation of the financial system, we propose the use of SFC models coupled with the IO model to analyse the second-order effects of a change in the economy. SFC models explicitly take into account the income redistribution and can provide a consistent accounting framework for describing the effects of an economic shock. Whereas, IO models are appropriate to analyse the relationship between the economy and ecological subsystems through the EE-IOTs and are particularly compatible with LCA.

3

Proposed method

This chapter presents the methodology developed in the thesis[7]. It is divided into five parts, starting by introducing the consequential life cycle assessment as an interdisciplinary approach, where an economic model is coupled to obtain the environmental consequences of an economic perturbation. Section 3.2 presents the relationship between the first step of the conventional life cycle assessment methodology, namely the goals and scope, with a focus on defining the system boundaries and on the functional unit. Section 3.3 explains the five steps of the proposed method for obtaining the life cycle inventory: defining the exogenous perturbation, defining the pertinent transactions and institutional sectors, modeling the monetary distribution, ensuring the stock-flow consistency, and modelling the monetary re-distribution. Section 3.4 presents how the life cycle impact assessment is conducted here in this thesis. Finally, Section 3.5 explains the method for obtaining the "Stocks database".

3.1 Consequential life cycle assessment – an interdisciplinary approach

The methodology proposed in this thesis is based on the conventional LCA framework defined by the international standards ISO 14040/44 (2006), as presented in the first Chapter. Thus, here, the four phases from ISO14040/44 (as presented in Figure 1.8) are also kept so that the method is consistent with the common framework currently applied by the practitioners. The most significant difference lies in the second phase (life cycle inventory – LCI), where an economic model is coupled with the conventional LCI, as explained in Chapter 2. In this

[7] The abbreviations frequently used in this chapter are: life cycle inventory (LCI), stock-flow consistent (SFC), transaction-flow matrix (TFM), households (HH), general government (GG), rest of the world (ROW), financial corporations (FC), non-financial corporations (NFC)

approach, environmental and socio-economic impacts can be assessed, prom the life cycle point of view.

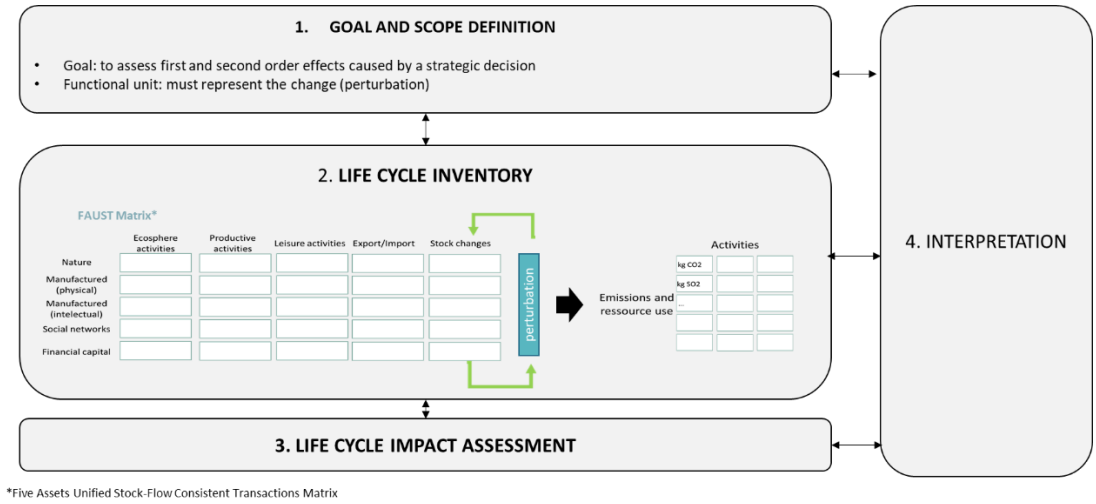

Figure 3.1 | General framework of the CLCA proposed methodology

Figure 3.1 presents the general framework of the CLCA method proposed in this thesis. The first phase consists in defining the goal and scope of the study. For this purpose, the reasons for choosing the approach must be described, as in a traditional LCA. In this phase, the functional unit must be defined and must represent the change that is studied by the CLCA, as well as the timeframe of the study. The other features of this first part do not significantly differ from a traditional LCA and for this reason are not going to be detailed here.

The second phase analyzes the life cycle inventory. This phase is the most challenging from the consequential point-of-view because the 'indirect effects' must be included here. It is thus in this phase that a SFC-IO model is integrated, as detailed in the following sections. It is worth highlighting that the major contribution of the thesis lies in this phase of the methodology.

Once the inventory is obtained, the impact assessment can be conducted (phase 3), in function of the substances and resources that were assessed in the second phase. Lastly, phase 4 supports the previous three steps by promoting an iterative system between each phase.

3.2 Goals and scope definition

According to ISO 14040, the goal of an LCA defines the intended application, reasons for carrying out the study, the audience, and communication objectives. The methodology proposed here keeps the same requirements, as no particularity is added to this point. For the scope definition, ISO 14040 requires, among others, the definition of the product system, system boundaries and functional unit, discussed in the following sections.

3.2.1 Product system and system boundaries

ISO 14040-44 series states that "ideally, the product system should be modelled in such a manner that inputs and outputs at its boundary are elementary flows". "Elementary flow" is the ISO 14040 term for a flow "drawn from the environment without previous human transformation" or "released into the environment without subsequent human transformation" (ISO 14040, clause 3.12), distinguishing between economic activity and the environment/nature. This has been challenged by Weidema et al. (2018), who suggest that the boundary between product systems and environment as defined in ISO 14040-44 series does not facilitate the inclusion of different feedback loops between environment and human activities. Therefore, it is still common practice to include only the suppliers that change their production in response to the change in demand for a product.

The suppliers are identified by tracing each required product input backwards through the chain of activities. The cost for one activity is a source revenue for the supplying activity. For each activity, a part of the revenue leaks out as payments to employees and entrepreneurs, taxes, and resource rents (together known as "primary factors" or "value added"). In a closed steady-state system, all the original revenue must eventually leave the system as payments to primary factors, which are not traced further upstream, thus providing a clear delimitation of the activities included in the system.

The activities included in the product system are thus limited to those that react to the change in revenue, corresponding to the first-order effects of the original spending, while keeping overall spending constant ("ceteris paribus" assumption). Implicitly, when comparing products with different prices, a product system will include first-order price rebound effect, while excluding second-order effects, such as changes in consumption patterns that may result from the redistribution of the initial spending on the population groups that receive the primary factor income, or second order effects of stimulating specific activities, such as education, research, and technological development (Weidema et al., 2015).

While this delimitation to first-order effects provides an unambiguous delimitation of the product systems, it is nevertheless arbitrary and thus an inherently normative delimitation. The unwillingness to include second-order effects in LCA may come from the intuition that this could lead to an infinite expansion of the system to include all consequences of all activities 'until the end of the World' (Weidema et al., 2015). In this thesis, we go beyond normative system boundaries and include income redistribution effects, a type of second-order effects as defined in Chapter 2 (See Glossary).

3.2.2 Functional unit

ISO 14040-44 series defines functional unit as "the quantification of the identified functions" as performance characteristics to provide a reference unit. However, the LCA ISO standards do not provide any clear definition on the specificities for the consequential approach, as also mentioned in Section 1.3, p.17. Weidema et al. (2003) proposed a method for defining the consequential functional unit, where, in addition to providing a reference unit and enough elements for comparing different alternatives, as required in ISO14040-44, it must also reflect the potential substitutions that the decision maker can influence. The latter is particularly pertinent when the CLCA studies the replacement of a set of products with another product or group of products fulfilling the same requirements.

Recently, in their review, Schaubroeck et al. (2021) distinguished the definition of the functional unit for both attributional and consequential approaches. According to them, the functional unit in CLCA "analyses how the decision changes the human/industrial system and its environmental impact at a global level", meaning that the functional unit must represent the studied decision, in terms of the changes proposed at a global level.

In practice, the functional unit of new policies must reflect the changes in demand occurring as a result of the new policy. When substitutions are involved, they must be clearly described and represented in the functional unit, so that the comparisons are consistently obtained.

3.3 Life cycle inventory

3.3.1 Proposed model: conceptual description

The idea of developing a model combining aspects from input-output analysis and stock-flow consistent, and process models, such as LCA, is to benefit from their advantages and provide a complete and detailed tool to help decision-making. Five Assets Unified Stock-flow Transactions (FAUST) represents this **conceptual idea** developed initially by Weidema (2019). This model would have as many layers as needed to represent the perturbation for the purposes of the user, for example, one of these layers could be the dry mass, to represent the physical flows and stocks of a perturbation (Weidema, 2019).

Table 3.1 | FAUST matrix (Weidema, 2019)

Assets/activities	Ecosphere activities	Productive activities	Leisure activities	Export/ Import	Stock changes
Natural resources	+ Natural ecosystem services	- Natural ecosystem services	- Ecosystem services	± Biogeochemical flows	± Natural resources
Manufactured (physical)	+ Deposition on cultivated areas and manufactured structures	± Manufactured physical goods	-Manufactured physical goods	± Manufactured physical goods	± Manufactured physical goods
Manufactured (intellectual)		± Intellectual capital	- Intellectual capital	± Intellectual capital	± Intellectual capital
Human capabilities	± Vectors of human health	- Work hours ± Human capabilities + Occupational health vectors ± Lost hours	- Leisure hours ± Human capabilities + Occupational health vectors ± Lost hours	± Migration	± Human capabilities
Social networks		± Social networks - License to operate	± Social networks - Culture heritage	± Cross-border networks	± Social networks
Financial capital*		- Labor pay - Interest ± Taxes ± Savings ± Voluntary transfers ± Untaxed rent ± Underpaid labor	+ Labor income + Interest ± Savings ± Voluntary transfers ± Untaxed rent ± Underpaid labor	± Foreign investment ± Voluntary transfers	+Credit - Debit

**Focus of the works developed in the thesis*

In a FAUST matrix, as presented in Table 3.1, the columns represent the activities that affect each of the six assets (or capitals): natural resources, manufactured capital, human capital, social network capital, and financial capital. The activities that compose the conceptual idea of FAUST are ecosphere activities, productive and leisure activities, export, import, and stock changes.

This is a holistic way to map the interactions between resources and uses consumed/produced by human activities to respond to the needs of the Society. In 2011, the International Integrated Reporting Committee (IIRC) shed light on the need to report on how an organization uses and/or impacts each of the six capitals to understand how sustainable their activities are (IIRC, 2011).

Following this integrated view, the Life Cycle Initiative (hosted by UNEP) proposes a way to link LCA with the Sustainable Development Goals based on a standard "sustainable wellbeing" indicator (Life Cycle Initiative, 2020; Weidema, 2022). This common endpoint indicator is constructed from the impact pathways, which represent the causal relationships between pressure indicators and midpoint impacts. The pressure indicators are quantified in

terms of their impacts on instrumental values (asset losses related to natural resources, manufactured, human, social network and financial capitals) and impacts on intrinsic values (intrinsic activity benefits, for example, the natural, cultural and intellectual heritage). The linkages between the interactions of the six capitals and the sustainable development are thus established.

From a practical point of view, the conceptual framework of FAUST relates to stock-flow consistent (SFC) models, as FAUST must respect the resource constraints. For example, the amount of wood taken from nature to construct a wall structure (negative sign in natural resources, ecosphere activities) must equal the amount of wood used by productive activities in manufactured capital. A balance is accordingly conducted for each layer (time, money, mass), considering that every output of an asset in one column must be an input in the same row but for another activity.

Considering the complexity of FAUST for taking into account all the real interactions, this thesis focuses on the financial capital, which intermediates the other activities and thus can track the changes in flows and, consequently, the change in stocks (Weidema, 2022). The closest representation of FAUST in SFC models is the Transaction Flow Matrix (TFM). In a TFM the flows and the changes in stocks are accounted for (Godley and Lavoie, 2007).

Combining elements from IOA and SFC has been conducted in previous research. For example, Berg et al. (2015) present a methodology for modelling different nature of flows (hybrid IOT), based on an IO-SFC model, and apply the methodology in an economy composed of two sectors. In this thesis, we combine the methodology proposed by Berg et al. (2015) for assessing the first-order effects with environmentally extended multi-regional input-output (EE MRIO) tables, and we go further to include the second-order effects, as we call 'income (re)distribution model'.

The EE MRIO table selected for the purpose of this thesis is the EXIOBASE[8], which is an open-source EE MRIO database developed by a consortium of several research institutes, financed by consecutive projects under the 7th framework program of the European Commission. The first version of EXIOBASE (EXIOBASE 1) was developed from 2007 to 2011 as a result of the EXIOPOL project (de Koning et al., 2011) and covers the year 2000, 43 countries, 1 rest of world region, 200 products, 163 industries, 15 land-use types, 48 types of raw materials, and 172 types of water used. In 2013, EXIOBASE 2 was launched as an outcome of the CREEA project (Tukker et al., 2013), covering the year 2007, with the same characteristics as the previous version, however, covering additional 4 rest of world regions.

The most recent version of EXIOBASE (EXIOBASE 3) was developed within the DESIRE project (European Commission, 2016). This version presents the EE MRIO tables in monetary and hybrid forms, and data is available for the period from 1995 to 2011. It covers 44 countries,

[8] More information and data download are available at: https://www.exiobase.eu/

5 rest of the world regions, 164 industries, 200 products, 3 employment skill levels per gender, 417 emission categories and 662 materials and resources categories. The monetary data series are available in the python module *pymrio* (Stadler, 2021), in which they have included estimates based on a variety of supporting data, such as trade and macro-economic data, going up to 2022.

As stated in Chapter 2 (Section 2.2.3), there are many ways for building an input-output table from supply and use tables (SUT). Table 3.2 summarizes the main characteristics of the EXIOBASE versions.

Table 3.2 | Characteristics of monetary and hybrid versions of EXIOBASE

	Monetary IOT	**Hybrid IOT**
Latest version		
Zenodo (pymrio)	EXIOBASE v.3.8.1	Not available
Website	EXIOBASE 3.4	EXIOBASE 3.3.18
Temporal coverage	1995 - 2021	2011
Aggregation	Industry-by-industry (product sales product sales assumption) Product-by-product (industry technology assumption)	Industry-by-industry (by-product technology assumption)
Technological coverage	163 industries, 200 products	164 products in the HIOT, 200 products in the SUTs
Geographical coverage	44 countries, 5 rest of the world regions	43 countries, 5 rest of the world regions
Extensions	*Zenodo pymrio version* **Satellite extension** Production-based accounting and consumption-based accounting, for both: - 9 value-added categories - 14 employment categories - 423 emission categories - 667 resource categories **Impacts extension** Production-based accounting and consumption-based accounting, for both: - 100 impact categories *Website version* **Satellite extension** - 9 value-added categories - 14 employment categories - 417 emission categories - 662 resource categories	*Website version* - 7 value-added categories - 14 employment categories - 39 resource categories - 5 land uses - 66 emission categories - 20 waste types (use, supply, packaging and stocks) - 8 crops

Ideally, when conducting an LCA it is recommended to use the product-by-product input-output tables, and for the consequential approach, the 'by-product technology' (see Section 2.2.3). Nonetheless, as shown in Table 3.2, the only version covering the latter is the hybrid version providing data from 2011. Therefore, considering that the temporal coverage of *pymrio version* is more appropriate for the case study, the **monetary input-output table from EXIOBASE 3.8.1** (hereafter EXIOBASE) was selected for conducting the modelling presented in this thesis, despite the fact that it violates some of the desired characteristics of consequential modelling.

With regard to the environmental extensions, two types are available: production-based accounting (PBA) and consumption-based accounting (CBA). The first one accounts for the production activities occurring within the borders of a country, while CBA considers also the environmental pressures embodied in trade (imports and exports) (Stadler et al., 2015). In the methodology developed in this thesis, the environmental impacts are calculated by multiplying the change in outputs (obtained by the Leontief's inverse, see Sections 3.3.3 and 3.3.4) by a normalized environmental coefficients matrix, which could be CBA or PBA. The change in total outputs reflects the affected chain of products and services (occurring within the national territory but also elsewhere), therefore, multiplying the change in total outputs by the PBA emissions would reflect direct and indirect emissions (and be equivalent to the CBA emissions). This is because each product is characterized by its own domestic and imported inputs, which are also characterized by their domestic and imported inputs (and so on). Therefore, for avoiding double-counting, in this thesis**, the PBA was selected for obtaining the environmental impacts.** A sensitivity analysis on the GHG emissions was also conducted to compare the results with the hybrid version (see Chapter 5, Section 5.2).

Figure 3.2 presents the general framework of the proposed method, which consists of five steps. The first thing to do is to define the exogenous perturbation, accordingly to the goals of the study. The perturbation must represent the functional unit of the study. More details are provided in Section 3.3.2. The second step is to define the transactions that will be part of the study and also to select the institutional sectors that are pertinent for the study (Section 3.3.3). The third step is the integration of a monetary distribution model, which will be detailed in Section 3.3.4. The fourth step (Section 3.3.5) consists of accounting for the changes in flows in a TFM and analyzing the changes in stocks that will affect another round of distribution, going back to step 3. The link between steps 4 and 3 can be considered as a fifth step, as presented in Figure 3.2.

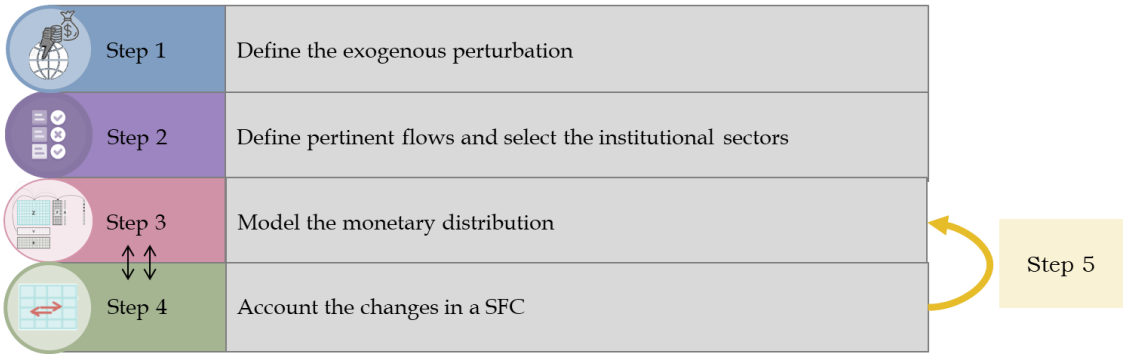

Figure 3.2 | Step-wise procedure of the proposed method

3.3.2 Step 1: Define the studied exogenous perturbation

An economic perturbation is defined as any change that affects the economy (Mankiw, 2009). The exogenous perturbations occur outside the industry or country but can have effects on the markets within an industry or a country (UNESCWA, 2020). Examples of exogenous perturbations are public policies changing taxes or fiscal incentives.

This step is aligned with the definition of goals and scope of the study (step 1 from the general LCA framework provided in ISO 14040/44). The functional unit represents the economic perturbation and it must be quantified according to the size and level of aggregation of the IOT. Ideally, the products that are impacted should be endogenized by using the most realistic marginal data to represent the life cycle stages of each product or services (foreground data).

In the case of this thesis, the products affected by the exogenous perturbation were selected from the activities that are included in EXIOBASE 3. The complete list of activities covered by EXIOBASE is available in Appendix 2.

3.3.3 Step 2: Define the pertinent transactions and institutional sectors

A TFM is able to include as many transactions as needed to represent the economy accordingly to the needs of the study. The selection of the transactions is thus based on the purpose of the study. Godley and Lavoie (2007) provide in their book several examples of situations, from simplified to more sophisticated ones, where the transactions and the sectors are selected properly. A proof of concept of the (re)distribution model is presented in a paper supplementary to this thesis[9] where the goal of the study was to test the method into a simplified closed economy composed of six industries, banks, and three level of income households. In the simplified model, the selected transactions were based on the simplified

[9] The article where the proof of concept of the (re)distribution model is (Almeida et al., 2022)

model from Godley and Lavoie (2007), called *bank-money world* (BMW) model. However, for the purpose of the study, not all transactions presented in BMW model were included, for example, depreciation and investment were not taken into account.

The main internationally recognized texts that guide the macro-economic studies are the European System of Accounts (ESA), from 2010, also known as ESA2010 (European Commission, 2013), the System of National Accounts (SNA), from 2008 (United Nations, 2008), and the Balance of Payments (BoP) and International Investment Position (IIP) Manual (BPM6), from the International Monetary Fund (IMF) (IMF, 2009). Eurostat database (Eurostat, 2022) provides open-source datasets that are consistent with these accounting methodological approaches for the transactions as well as the balance sheets of the countries.

Institutional units are distinguished from sectors, as follows: *an institutional unit is an economic entity capable of owning goods and assets, of incurring liabilities and of engaging in economic activities and transactions with other units in their own right* (European Commission, 2013). Institutional sectors, on the other hand, *are groups of institutional units with similar economic forms of behaviour characterised by their main function and the nature of their activity* (INSEE, 2016). Therefore, resident institutional units are grouped into five domestic sectors: non-financial corporations (NFC), financial corporations (FC), general government (GG), households (HH), non-profit institutions serving households (NPISH). Non-residential units are grouped into the rest-of-the-world (ROW) sector.

In this thesis, the first criterion for selecting the transactions that are included in the proposed model is based on the availability of data. As we use EXIOBASE, all the flows that are provided in the database are included. The flows that provided directly by EXIOBASE are listed here below:

- Taxes less subsidies on products purchased
- Other net taxes on production
- Compensation of employees; wages, salaries, & employers' social contributions: Low-skilled, Medium-skilled and High-skilled
- Operating surplus: Consumption of fixed capital
- Operating surplus: Rents on land
- Operating surplus: Royalties on resources
- Operating surplus: Remaining net operating surplus
- Final consumption expenditure by households
- Final consumption expenditure by non-profit organisations serving households (NPISH)
- Final consumption expenditure by government
- Gross fixed capital formation
- Changes in inventories
- Changes in valuables

The part of the transactions obtained directly from EXIOBASE that occur between institutional sectors is presented in Figure 3.3.

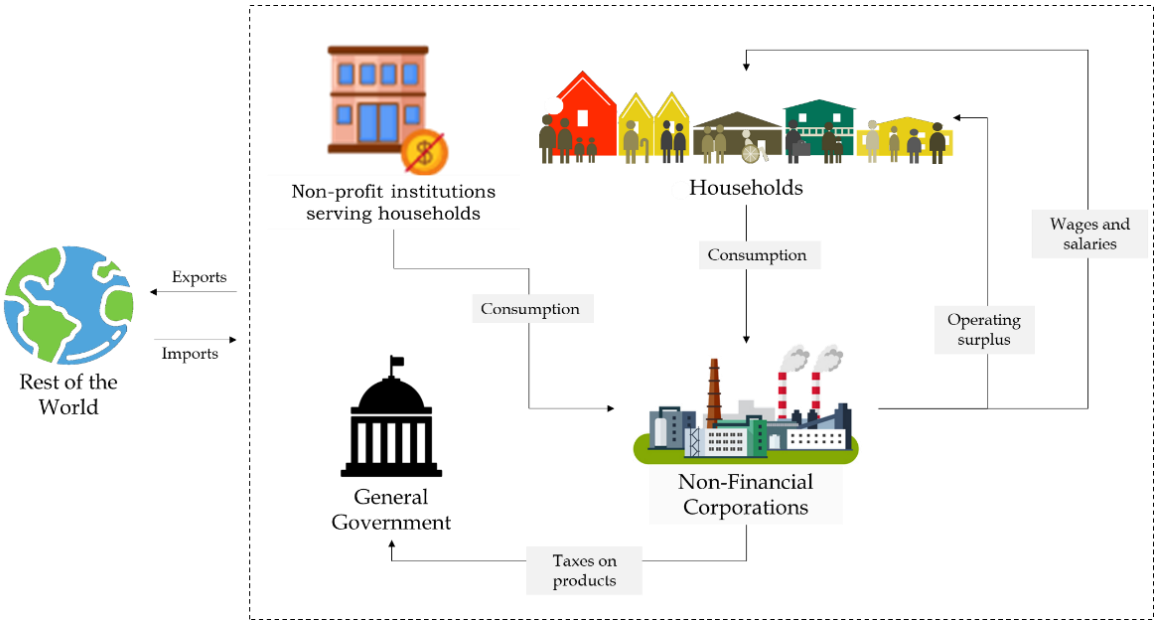

Figure 3.3 | Transactions from EXIOBASE between the intuitional sectors

The second criterion is the materiality of the transactions for the whole studied economy and how they are supposed to change in function of the studied change. To help to identify who receives and who pays the money in each account, a TFM of France for 2020 was obtained from Eurostat datasets[10] (see Appendix 3). The TFM is based on the non-financial and financial transactions from the System of National Accounts (SNA), available in Eurostat database.

In order to understand the most representative transactions in the French economy, the Table 3.3 presents the contribution of each transaction to total uses and resources of each institutional sector. The values were obtained based on the contribution of each transaction to total transactions of the sector (from Appendix 3). For example, final consumption expenditure represents 53% of total resources of non-financial corporations (NFC), 36% of total use the general government (GG), 53% of total uses of households (HH) and 55% of total use of non-profit institutions serving households (NPISH). In this table, all transactions that represent more than 5% of total uses and/or resources for each institutional sector are highlighted and considered as significant (based on expert's opinion).

[10] Eurostat datasets (available at https://ec.europa.eu/eurostat): "nasa_10_nf_tr" for non-financial transactions and "nasa_10_f_tr" for financial transactions.

Table 3.3 | Materiality of the flows in France's economy (based on 2020)

	NFC		FC		GG		HH		NPISH		ROW	
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res
Final consumption expenditure	-	53%	-	-	36%	-	53%	-	55%	-	-	-
Gross capital formation	9%	16%	5%	-	5%	-	6%	-	5%	-	-	-
Exports of goods and services	-	22%	-	-	-	-	-	-	-	-	78%	-
Imports of goods and services	22%	-	-	-	-	-	-	-	-	-	-	79%
Value-added, gross	26%	0%	0%	20%	0%	25%	0%	15%	0%	41%	-	-
Wages and salaries	18%	-	9%	-	13%	-	1%	39%	27%	-	2%	0%
Employers' social contributions	6%	-	4%	-	6%	-	0%	14%	9%	-	1%	0%
Taxes on products	8%	-	-	-	-	19%	-	-	-	-	-	0%
Other taxes on production	2%	-	2%	-	1%	7%	1%	-	1%	-	-	0%
Subsidies on products	-	1%	-	-	1%	-	-	-	-	-	0%	-
Other subsidies on production	-	1%	-	0%	3%	0%	-	0%	-	2%	1%	-
Interest	2%	1%	23%	32%	3%	0%	1%	1%	0%	1%	6%	7%
Distributed income of corporations	5%	4%	8%	11%	-	1%	-	2%	-	0%	7%	4%
Reinvested earnings on direct foreign investment	0%	0%	0%	1%	-	0%	0%	0%	0%	0%	1%	1%
Other investment income	0%	0%	15%	4%	0%	0%	0%	2%	0%	0%	0%	0%
Rents	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-	-
Current taxes on income, wealth, etc.	1%	-	3%	-	0%	21%	11%	-	0%	-	0%	0%
Social contributions	-	0%	-	8%	-	28%	21%	0%	-	0%	0%	1%
Social benefits other than social transfers in kind	0%	-	8%	-	30%	-	0%	21%	1%	-	1%	1%
Other current transfers	1%	1%	22%	22%	5%	1%	3%	3%	2%	54%	2%	6%
Adjustment for the change in pension entitlements	0%	-	0%	-	0%	-	0%	0%	0%	-	0%	0%
Capital transfers	0%	1%	0%	1%	2%	1%	1%	0%	0%	2%	0%	0%
Acquisitions less disposals of non-financial non-produced assets	0%	-	0%	-	0%	-	0%	-	0%	-	0%	-

Notes: Use : uses ; Res : resources

As observed in the previous table, the most significant transactions are:

- Final consumption expenditure, which is included in EXIOBASE3
- Gross capital formation, which is included in EXIOBASE3
- Exports of goods and services
- Imports of goods and services
- Value-added, gross
- Wages and salaries, which is included in EXIOBASE3
- Employers' social contributions, which is included in EXIOBASE3 (aggregated with wages and salaries)
- Taxes on products, which is included in EXIOBASE3
- Interest payments
- Distributed income of corporations
- Property income attributed to insurance policy holders
- Current taxes on income, wealth
- Social contributions
- Social benefits other than social transfers in kind
- Other current transfers

Exports and imports of goods and services can be obtained from Exiobase, as shown in Figure 3.4. The left side of the Figure illustrates the inter-industry monetary inputs and outputs, also known as the technological matrix (Z matrix). Therefore, the transactions between other countries and the French activities that represent an input for the latter (in blue) are imports for France, from business-to-business (B2B). On the other hand, the transactions between other countries and French activities that are outputs for France (in yellow) are exports, also B2B. The right side of Figure 3.4 presents the final demand (FD) matrix. The transactions that are a demand from French institutional sectors and supplied by other countries (in pink) are imports from business to consumer (B2C). The transactions that are demands from institutional sectors of other countries and supplied by French activities (in purple) are considered as exports, also B2C.

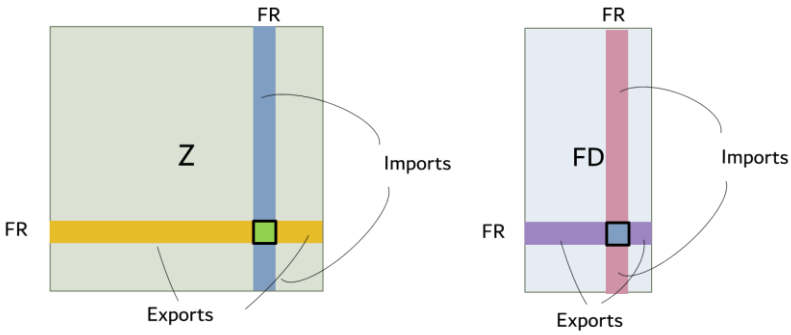

Figure 3.4 | Imports and exports in EXIOBASE (B2B on the left side and B2C on the right side)

The next transaction listed as possibly pertinent for including in the study is the gross value-added, which is defined as the balance of the production account, thus, can be obtained from other transactions (production minus intermediate consumption).

Interests are transactions between FCs and the other institutional sectors and are obtained in function of the changes in stocks. This account is included in the proposed method and plays an important role in linking the distribution rounds, as Section 3.3.6 explains.

Distributed income of corporations are dividends paid by corporations to their shareholders and the withdrawals for their own use from the income of quasi-corporations (European Commission, 2013). They appear in the table relatively relevant for FCs, which pay and receive the money. They are not integrated into the model because the main part of these transactions occurs within FC (+ and – for FC).

Other investment income corresponds to income coming from investments other than interests, distributed income of corporations, and reinvested earnings on foreign direct investments. It includes total primary incomes received from the insurance technical reserves, the income payable on pension entitlements, dividends attributable to collective investment fund shareholders and investment income attributable to collective investment fund shareholders. The most affected sectors are financial corporations (insurance companies) and

households. Depending on the goal of the study, this account can be included. This could be the case when studying a new policy that affects insurance policies and technical reserves.

Current taxes on income and wealth and social contributions are very representative of the government accounts. For new policies, they should be included. They are obtained by multiplying the taxes rate and the social contributions rate to the changes in income.

Social benefits other than social transfers in kind are the social security and social assistance benefits (in cash) and other insurance benefits paid by the government to households. These transactions might be more or less meaningful depending on the country's social security system. In France, it is particularly relevant thus it must be included in the model.

Another current transfer is a generic account for all current transfers that were not included in other categories. It comprises net non-life insurance premiums and claims, current transfers within general government (from/to central, state, local government), current international cooperation, in the case of foreign investment on policies, for example, and miscellaneous current transfers. The latter is a broad account for accounting for voluntary contributions to NPISHs, money transfers between households that occur within or outside the country (for example, money transfers for family members living abroad), fines, and penalties. Since these transactions differ strongly in nature, it is not recommended to include them in the study, with the exception of the cases where their dynamics are linked with the perturbation.

3.3.4 Step 3: Model monetary distribution

The distribution model is based on the input-output analysis calculation framework. Firstly, the technical coefficients matrix (A) must be defined. It contains the ratio of inputs from the industry "i" to the industry "j" (z_{ij}) in relation to the total outputs of industry "j" (x_j) and it is obtained by Equation 3-1. The dataset from EXIOBASE provides directly this matrix in the monetary version.

$$A = \frac{a_{ij}}{x_j} \qquad \text{Equation 3-1}$$

A marginal change in final demand will affect the direct and indirect input requirements, obtained by Leontief's inverse $L = (I - A)^{-1}$. Therefore, the changes in the total outputs vector (x'), also known as the scaling factors, is calculated by Equation 3-2.

$$x' = L\,F \qquad \text{Equation 3-2}$$

These changes in total industries' outputs affect the amount of money received by the industries' employees, keeping the same proportions between income groups within each

industry as before the shock. This can be understood either as a proportional change in the number of workers in the affected industries, or as proportional changes in wages. This impact is computed by multiplying the normalized gross value-added coefficients matrix (B), where $\tilde{b}_j = \frac{b_j}{xj}$, by the changes in total outputs vector (x'), as presented in Equation 3-3.

$$G = \tilde{B}x' \qquad \text{Equation 3-3}$$

Matrix G represents the changes in primary factor income, i.e., the wages and salaries, operating surplus and taxes paid industry "j".

The LCI is obtained from expanding the matrix G to include environmental information. For that, E represents the matrix containing the substance emissions and the natural resources associated with each activity. Similarly to gross value-added, a normalized environmental coefficients matrix ($\tilde{E}$) is needed, where $\tilde{e}_j = \frac{e_j}{xj}$. Therefore, the LCI, represented by matrix D, is obtained by multiplying the $\tilde{E}$ matrix by new outputs, as presented in Equation 3-4.

$$D = \tilde{E}x' \qquad \text{Equation 3-4}$$

3.3.5 Step 4: Ensure stock-flow consistency

In each round of distribution, changes in flows and stocks must be accounted for in a Transaction Flow Matrix (TFM), as presented in Table 3.4. This step occurs in parallel to step 3 to ensure the consistency of all transactions, starting from the perturbation. The challenge lies in knowing who receives the money and who pays for it.

In EXIOBASE pymrio version, the value-added transactions include "taxes less subsidies on products purchased", "other net taxes on production", "compensation of employees: wages, salaries, & employers' social contributions", disaggregated into three income levels: low-skilled, medium-skilled and high-skilled; and "operating surplus", disaggregated into four categories: "consumption of fixed capital", "rents on land", "royalties on resources" and "remaining net operating surplus". Taxes and compensation of employees have a clear agent receiving side of the transaction, as presented in Table 3.4.

Table 3.4 | Transaction Flow Matrix

Transaction	NFC	FC	GG	HH			RoW	Sum
				LS	MS	HS		
Final consumption expenditure	$+C^R{}_{NFC}$			$-C^U{}_{HH,LS}$	$-C^U{}_{HH,MS}$	$-C^U{}_{HH,HS}$		0
Gross capital formation	$+GCF^R{}_{NFC}$		$-GCF^U{}_{GG}$	$-GCF^U{}_{HH,LS}$	$-GCF^U{}_{HH,M}$	$-GCF^U{}_{HH,H}$		0
Exports of goods and services	$+Ex^R{}_{NFC}$						$-Ex^U{}_{ROW}$	
Imports of goods and services	$-Im^U{}_{NFC}$						$+Im^R{}_{ROW}$	0
Operating surplus	$-OS^U{}_{NFC} + OS^R{}_{NFC}$	$+OS^R{}_{FC}$	$+OS^R{}_{GG}$	$+OS^R{}_{HH,LS}$	$+OS^R{}_{HH,MS}$	$+OS^R{}_{HH,HS}$		0
Wages and salaries	$-W^U{}_{NFC}$			$+W^R{}_{HH,LS}$	$+W^R{}_{HH,MS}$	$+W^R{}_{HH,HS}$		0
Employer's social contributions	$-ESC^U{}_{NFC}$		$+ESC^R{}_{GG}$					0
Taxes on products	$-TxP^U{}_{NFC}$		$-TxP^R{}_{GG}$					0
Other taxes on production	$-OTx^U{}_{NFC}$		$-OTx^R{}_{GG}$					0
Interests on Loans	$-IL^U{}_{NFC}$	$-IL^R{}_{FC}$	$-IL^U{}_{NFC}$					0
Interests on Deposits	$+ID^R{}_{NFC}$	$-ID^U{}_{FC}$		$+ID^R{}_{HH,LS}$	$+ID^R{}_{HH,MS}$	$+ID^R{}_{HH,HS}$		0
Current taxes on income, wealth, etc.			$+TI^R{}_{GG}$	$-TI^U{}_{HH,LS}$	$-TI^U{}_{HH,MS}$	$-TI^U{}_{HH,HS}$		0
Social contributions			$+SC^R{}_{GG}$	$-SC^U{}_{HH,LS}$	$-SC^U{}_{HH,MS}$	$-SC^U{}_{HH,HS}$		0
Social benefits			$-SB^U{}_{NFC}$	$+SB^R{}_{HH,LS}$	$+SB^R{}_{HH,MS}$	$+SB^R{}_{HH,HS}$		0
Other current transfers			$+CT^R{}_{GG}$				$-CT^U{}_{ROW}$	0
Deposits	$-Dp^U{}_{NFC}$	$+Dp^R{}_{FC}$	$-Dp^U{}_{GG}$	$-Dp^U{}_{HH,LS}$	$-Dp^U{}_{HH,MS}$	$-Dp^U{}_{HH,HS}$	$-Dp^U{}_{ROW}$	0
Debt	$-Db^U{}_{NFC}$	$-Db^U{}_{FC}$	$+Db^R{}_{GG}$ $-Db^U{}_{GG}$	$+Db^R{}_{HH,LS}$	$+Db^R{}_{HH,MS}$	$+Db^R{}_{HH,HS}$	$-Db^U{}_{ROW}$	0
Sum	0	0	0	0	0	0	0	

The challenge is to identify the receiving and paying agents for the other transactions. Moreover, there is no information on the relationship between the two-hundred economic activities presented in EXIOBASE and the institutional sectors controlling them. For this reason, we developed an empirical matrix (Phi matrix) that attributes to each EXIOBASE activity the control of one or a combination of institutional sectors for France (as presented in

Appendix 4 – Phi matrix). This matrix was an effort to try to take into account the fact that the economic activities are also developed by other institutional sectors than NFCs, depending on their nature. However, adding this feature to the balances made it even more complicated since the alpha matrix was built upon estimated shares, adding uncertainty to the results, and not providing a more realistic picture of the economy. Indeed, this precision is not needed in this modelling approach as it is because the money received by the activities is distributed vertically to other accounts (wages, taxes, etc.) and then horizontally the same way for all activities regardless of the institutional sector that controls them.

For example, suppose that HH consume 10 units of a service that is 40% controlled by NPISHs and 60% controlled by NFCs. This activity used half of the received money to pay the wages of workers and the other half is used to pay taxes to the government. Figure 3.5 (a) illustrates the situation where the transaction is accounted for disaggregating the institutional sectors, represented by the green arrow (NFCs receive six units and NPISHs receive four units). Then, NFCs pay 3 units to workers (HH) and 3 units to GG and, analogously, NPISHs pay 2 units to HH and 2 units to GG (yellow arrows). The change in stocks is thus - 5 to GG and +5 to HH. Now, suppose that NFCs represent the sector that receives the money of the consumption of the service consumed by HH (green arrow in Figure 3.5 (b)). NFCs distribute the money as wages and taxes (blue arrows) to HH and GG (yellow arrows), respectively. The net balance in change in stocks is exactly the same: changes in stocks of -5 units for GG and +5 units for HH.

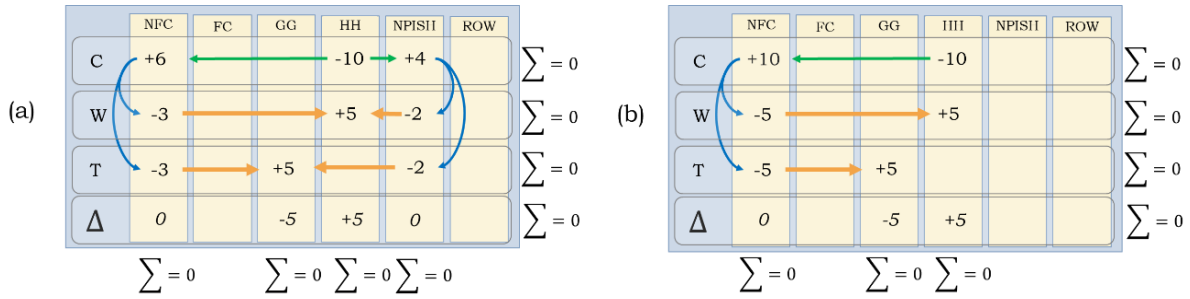

Figure 3.5 | Two situations for accounting the consumption of a service controlled by more than one institutional sector

The changes in stocks (net worth) are a result of the monetary balance in flows, i.e., it is the net lending or net borrowing value of each institutional sector. In this simple example provided in Figure 3.5, the changes in stocks would represent net lending money for GG and net borrowing money for HH. The net lending money could be transferred as deposits for the FCs, and the net borrowing money could be withdrawn from their own current account or a real loan could take place to finance the consumption. Either way, the changes in the net wealth of GG and HH must be represented as financial transactions with FCs in a second step, which is not illustrated in Figure 3.5.

Therefore, a common assumption is that NFCs receive all money from consumption, capital formation and exports and pay for the imports, and, as counterpart, they redistribute a part of the value-added to other institutional sectors. In the case of France, for example, the redistribution of GVA in 2020 follows the proportions: 10% for FCs, 44% for GG, 42% for HHs and 4% for NPISHs, obtained from the values presented in Appendix 3.

In our model, we follow this rationale, **NFCs receive all changes in transactions of final demand elements plus the exports, pay for the imports of products and redistribute part of the value-added trough the operating surplus.** The rates applied to distribute the operating surplus are obtained from the contributions of the institutional sectors to the gross value-added (GVA).

The operating surplus received by households must be disaggregated into the income groups. There are several possible ways for this to happen, which affect differently the net wealth of each income group and the following rounds of induced consumption. Here, three scenarios for a "whom-to-whom" transactions of operating surplus:

- **Scenario 1:** the operating surplus associated with each product is distributed to the three income groups following the same proportions as the wages and salaries are paid to each income group
- **Scenario 2:** all the operating surplus is received by high-skilled households
- **Scenario 3:** all operating surplus is saved by households (its aggregated form)

In Scenario 1, for the activities where there is no data on the compensation of employees and the activity presents an operating surplus, the allocation is conducted as if all operating surplus goes to the high-skilled income group. This happens in 51 activities, for example, membership organization services in Denmark.

As explained in Section 3.3.3, EXIOBASE database provides the information on main flows that are included in the proposed method. However, there is no information with regard to the stocks. For that, a stock database was built, as presented in Section 3.5.

The changes in stocks may induce consumption and/or investment, which result in environmental impacts. At the end of the first monetary distribution round, the cumulated money from households (in a positive exogenous shock) would result in a false increase in net wealth, because the money received from HH as wages is used to buy consumption goods and services. Therefore, the changes in stocks in the first round of each period are temporary and cause an induced effect, in which a monetary redistribution takes place.

3.3.6 Step 5: Model the monetary re-distribution

Households change their consumption according to their change in net worth from the previous round. In reality, households save a part of their additional income and another part is spent on consumption goods. This induced consumption includes the shifts in consumption

between industries due to the different spending patterns of the three income groups. Here a 'distribution period' includes the changes in the compensation of employees resulting from perturbation ("1st round") and the induced consumption resulting from the changes in income ("2nd round"), as Figure 3.6 illustrates.

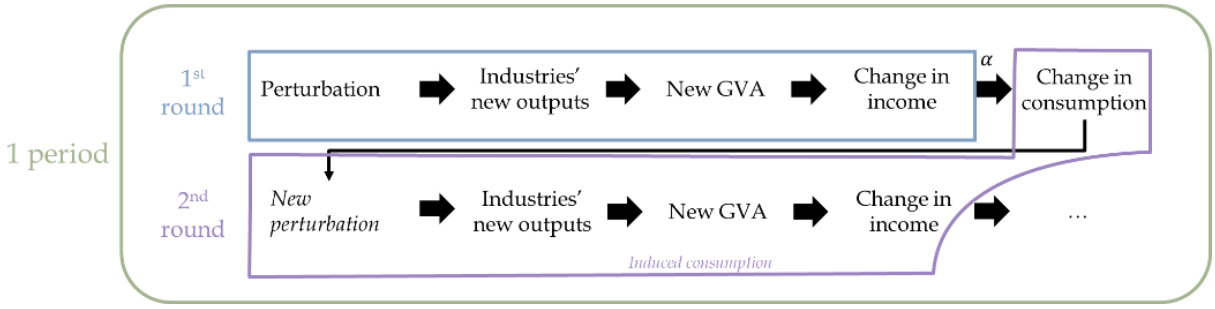

Figure 3.6 | Boundaries of distribution rounds and period

For the sake of simplification, here the households' consumption is only a function of labor income, while their property income is entirely reinvested. The change in final demand (F) is thus obtained from the consumption function described in Equation 3-5.

$$F = \tilde{C}.H \qquad \text{Equation 3-5}$$

The matrix $\tilde{C}$ represents the marginal consumption patterns, obtainable from national statistics. These matrixes must be disaggregated in function of the number of income levels of households and the number of activities that are included in the IOT. The H matrix represents the expenditure in the second round, i.e., the part of income of households that will be used for consumption in a second round ($H_i = Dp^U{}_i.\alpha_i$), where Dp^U represents the change in deposits accounted for in the previous round, α is the propensity to consume out of extra income, both disaggregated by income level. The change in deposits is recorded as a "use" in the TFM because it is temporarily transferred to their current accounts.

This induced consumption is the new perturbation vector for the next round, and repeatedly for redistribution rounds (r+1), as presented in Equation 3-6.

$$F^{r+1} = \tilde{C}\ H^r \qquad \text{Equation 3-6}$$

The changes in stocks (net wealth) of other institutional sectors can also present second-order effects, such as investment and growth. In this thesis, we limit ourselves to including the income redistribution effect and leave productivity growth and the inclusion of an investment function to future research.

3.4 Life cycle impact assessment

As explained in Section 3.3.4, the life cycle inventory is obtained by expanding the G matrix to include the substance emissions and resources consumption, also known as the biophysical stressors (E matrix). EXIOBASE 3 available in pymrio provides two types of environmental extensions: **substance emissions and resources consumption by activity (satellite dataset)** and **characterized impact indicators by activity (impact dataset)**. The latter presents the impact indicators already characterized by the regular LCIA methods, including 123 impact categories, from CML, Ecoindicator 99, ILCD, IPCC, and others. Satellite dataset one comprises 1090 substance emissions and natural resources consumption, among them carbon dioxide, methane, particulate matter emissions, water consumption, and many others. The complete list is available at *pymrio* website[11].

Theoretically, any LCIA method can be applied to characterize the emissions and resources that are included in the database. In this thesis, the developed methodology is applied in a case study in the construction sector, therefore the environmental impact assessment prioritizes the impact categories that are particularly pertinent for the construction sector, namely the energy consumption, GHG emissions, and wastes.

Concerning GHG emissions, there are two ways for obtaining this indicator in EXIOBASE: calculating the GHG emissions by applying the appropriate characterization factors to the emitted substances from the satellite dataset, or selecting the climate change indicator from the impact dataset. The latter includes 10 climate change indicators, of which three from the ILCD method (one midpoint and two endpoint: human health and ecosystems); one GHG emissions indicator obtained by using the characterization factors from the Fifth IPCC Assessment Report (AR5), with the global warming potential (GWP) of 100 years; and five GHG emissions indicators from the CML method (problem oriented approach), being one baseline and four non-baseline, varying the time horizon of the GWP (20, 100 and 500 years).

In theory, if we apply the same characterization factors as the methods selected by EXIOBASE, the results will be the same for the two options. For this reason, the choice made in this thesis was to select one of the climate change indicators from the impact dataset, namely the **climate change midpoint from ILCD, with a GWP of 100 years**, which is the one required in the environmental profile declaration of construction products.

For energy consumption, there is no impact category already assessed in the impact dataset. However, recently, an update of the pymrio characterization factors was launched for linking EXIOBASE with the IMPACT World + method[12]. In this up-to-date matrix, there are

[11] https://pymrio.readthedocs.io/en/latest/notebooks/working_with_exiobase.html

[12] Available at: https://zenodo.org/record/4739143#.YlKb2bUzY2x (from May 2021)

characterization factors for accounting for the energy indicator called **fossil and nuclear energy use**, which characterizes the energy consumption not only from the energy inputs from nature, but also for the extraction of fossil fuels (domestic used and unused flows). These characterization factors were used in the thesis, as presented in Table 3.5.

Table 3.5 | Characterization factors for the indicator 'fossil and nuclear energy use (TJ deprived)'

Stressor	Unit	Characterization factor (TJ/unit)
Energy Inputs from Nature: Total	TJ	1
Domestic Extraction Used - Fossil Fuel: Total	kton	9.9
Unused Domestic Extraction - Fossil Fuels - Anthracite	kton	19.1
Unused Domestic Extraction - Fossil Fuels - Coking coal	kton	0
Unused Domestic Extraction - Fossil Fuels - Crude oil	kton	45.8
Unused Domestic Extraction - Fossil Fuels - Lignite/brown coal	kton	9.9
Unused Domestic Extraction - Fossil Fuels - Natural gas	kton	40.3
Unused Domestic Extraction - Fossil Fuels - Natural gas liquids	kton	40.3
Unused Domestic Extraction - Fossil Fuels - Other bituminous coal	kton	18
Unused Domestic Extraction - Fossil Fuels - Peat	kton	9.9
Unused Domestic Extraction - Fossil Fuels - Sub-bituminous coal	kton	9.9

The monetary IOT from EXIOBASE available for 2020 in *pymrio* does not provide any information on waste mass-produced. The hybrid version, on the other hand, provides information of wastes supplied and used by each activity and by final demands (Stadler et al., 2018), however, the latest version of EXIOBASE covers the year 2011. Wastes are defined in EXIOBASE as "a material for treatment that includes all the materials that need further reprocessing in order to be turned into new products, emissions, or stock addition in landfills" (Stadler et al., 2018). The data is available in the following forms: wastes supplied by activity, wastes supplied by final demand, wastes supplied from materials accumulated previously in the society, and the use of wastes by activities. The use side concerns the waste treatment activities, while the supply side concerns the other activities, households, non-profit institutions serving households, and general government as well.

Therefore, the wastes supply intensities (total produced mass per total monetary outputs) provided by activity from 2011 were used in the thesis. The list of types of wastes that are analyzed in the thesis is here below:

- Food wastes
- Manure
- Textile wastes
- Wood wastes
- Paper wastes
- Plastic wastes
- Glass wastes
- Ashes
- Steel, aluminium, lead, copper and non-ferrous wastes
- Precious metals wastes
- Construction materials and mining waste (excl. unused mining material)
- Oils and hazardous material wastes
- Sewage
- Mining waste
- Unused waste

3.5 Stocks database

The goal of building the 'Stocks database' is to provide information on who is affected by changes in stocks of institutional sectors included in the CLCA study. For that, a whom-to-whom matrix between institutional sectors and countries must be built, as illustrated in Figure 3.7. In this example, there are three countries (A, B, C) and five institutional sectors (NFC, FC, GG, HH, NPISH). The squares highlighted in yellow correspond to the domestic debt, while the white parts represent external cross-country debt. Each rectangle represents a debt relationship between the debtor (horizontal) and the creditor (vertical).

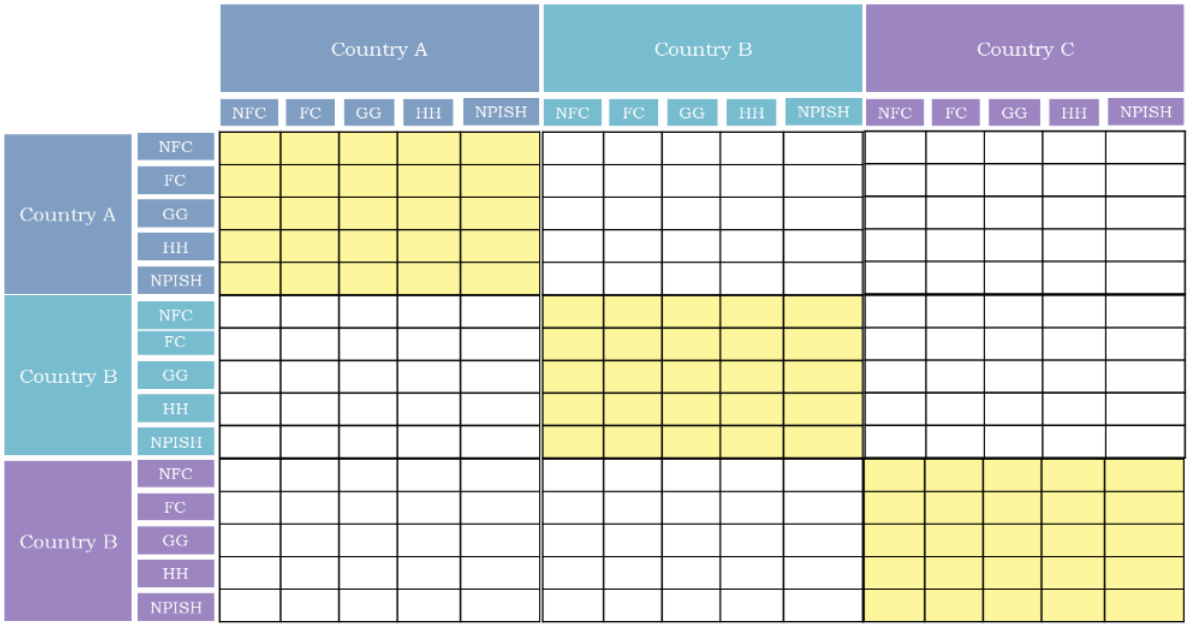

Figure 3.7 | Whom-to-whom matrix framework for debts

The idea is to get information from this matrix on the affected chain resulting from marginal changes in stocks. For example, if the government of country A takes loans, the matrix allows identifying who are the issuers of the loans (which institutional sectors and which country).

Background on foreign investment

Investors can invest their money by using different financial instruments[13]. For example, equities result in distributing the income of corporations, while deposits, debt securities, and loans give rise to interests paid/received (IMF, 2015). Since investments have no geographic boundaries, the financial instruments are classified following international standards. The sixth edition of the Balance of Payments and International Investment Position Manual (BPM6) provides the definitions that are used in the international accounts, where the investment is

[13] Financial instruments are defined as the financial contracts made between institutional units (IMF, 2009).

distinguished into five categories: direct investment, portfolio investment, financial derivatives, other investment and reserve assets (IMF, 2009).

'Direct investment' is a "*category of cross-border investment associated with a resident in one economy having control or a significant degree of influence on the management of an enterprise that is resident in another economy*", according to BPM6. The main instrument for direct investing is by means of buying equity of a company, more commonly made by companies that are creating branches in other countries. The worldwide statistics database concerning 'direct investment' is the Coordinated Direct Investment Survey (CDIS), with the goal of providing whom-to-whom cross-border data[14].

'Portfolio investment' is defined in BPM6 as *"crossborder transactions and positions involving debt or equity securities, other than those included in direct investment or reserve assets"*. The most common instrument of this category is buying equity securities of a company. Securities are debt and equity instruments that are negotiable, tradable, and present a monetary value, such as shares and bonds (IMF, 2009). The worldwide statistics database concerning 'portfolio investment' is the Coordinated Potfolio Investment Survey (CPIS), providing the economy's data on its holdings of portfolio investment securities, as equity and investment fund shares and debt instruments by maturity[15].

According to the BPM6, 'financial derivatives' cover the *financial instruments that are linked to another specific financial instrument or indicator or commodity and through which specific financial risks (such as interest rate risk, foreign exchange risk, equity and commodity price risks, credit risk, and so on) can be traded in their own right in financial markets*.

'Reserves' are defined in BPM6 as the "*external assets that are readily available to and controlled by monetary authorities for meeting balance of payments financing needs, for intervention in exchange markets to affect the currency exchange rate, and for other related purposes (such as maintaining confidence in the currency and the economy, and serving as a basis for foreign borrowing)*". They only comprise actually existing assets and must be defined in foreign currency. A common example is monetary gold belonging to monetary authorities (central bank) consisting of gold bullions readily available upon demand (liquidity)(IMF, 2009).

'Other investment' is a residual category, meaning that all transactions not corresponding to the characteristics of the other four categories are classified as "Other investment". Therefore, it includes currency and deposits, loans, and life insurances, for example, which represent some of the instruments that are affected by marginal changes in stocks.

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[14] CDIS data is available at: https://data.imf.org/CDIS

[15] CPIS data is available at: https://data.imf.org/CPIS

Cross-country whom-to-whom matrix

Ideally, the cross-country whom-to-whom matrix would be needed for each debt instrument, defined as transactions requiring the payment of principal value and interests in a defined moment in the future (IMF, 2015). However, due to a lack of data, a method was developed to build the cross-country whom-to-matrix for debt instruments, in general. Table 3.6 shows the main datasets and data sources used for the study. The references are international statistics datasets provided by international financial institutes as well as national statistics from national central banks and national institutes of statistics and economics (such as *Banque de France* and INSEE for France).

Table 3.6 | Main data sources for building the stock database

World Bank	**IMF**	**OECD**	**Eurostat**	**National sources**
-Quarterly external debt statistics (QEDS)	-Coordinated Portfolio Investment Survey (CPIS) -Exchange rates	-FDI statistics -System of national accounts (SNA) for non-EU countries	-System of national accounts for EU countries	- National databases - Central banks

Countries selection

The first challenge was to select the countries to be included in the data collection. Since the method developed in this thesis is applied in a case study in France, the French liabilities *vis-à-vi*s non-residents were used as a reference. The selection of countries was made using the geographical breakdown of 'Other investment' presented in the International Investment Position (IIP) of France, obtainable from the French central bank database. In this dataset, the liabilities of French monetary financial institutions other than central bank *vis-à-vis* thirty-three countries and regions are provided from 2008 to 2021.

'Other investment' is selected because it is the category where debt is the predominant instrument. For example, in 2020, the total economy of France had 2,843,159 million euros in liabilities as debt instruments, from a total 'other investment' of 2,855,116 million euros, representing more than 99%, while the debt securities represented 75% of total liabilities in portfolio investment (2,755,665 million euros out of 3,673,313 million euros).

Table 3.7 presents the percentages of France's liabilities to other countries. All countries that detained at least 1% of France's liability in 2020 were selected, with exception of offshore-financial centers[16]. The latter was excluded due to the difficulty of getting transparent and reliable data for them.

[16] Offshore financial centers are defined by the IMF "countries or jurisdictions with financial centers that contain financial institutions that deal primarily with nonresidents and/or in foreign currency on a scale out of proportion to the size of the host economy" (IMF, 2014).

Table 3.7 | Percentage of France's liabilities detained by other countries

Country	France's liability (%)
UK	29.0%
USA	15.0%
Germany	10.1%
Luxembourg	9.3%
Offshore-financial centers	6.4%
Netherlands	4.6%
Italy	4.4%
Switzerland	2.5%
Spain	2.4%
Ireland	2.3%
Belgium	2.3%
Japan	1.6%
Cut-off China	1.2%
Russia	0.9%
Sweden	0.3%
Poland	0.1%
India	0.1%
Turkey	0.1%
Romania	0.0%
Czech Republic	0.0%
Brazil	0.0%
Other countries	7.3%

In addition, the database also includes the world economies that are excluded by the cut-off criterion but represent an important trade relationship with France. The list of the added countries is India, Brazil, Poland, Canada, Russia and Australia. Therefore, in total, this stocks database comprises 19 countries namely (with the respective ISO 3166 codes):

- France (FR)
- United Kingdom (GB)
- United States of America (US)
- Germany (DE)
- Luxembourg (LU)
- Netherlands (NL)
- Italy (IT)
- Switzerland (CH)
- Spain (ES)
- Ireland (IE)
- Belgium (BE)
- Japan (JP)
- China (CN)
- India (IN)
- Brazil (BR)
- Poland (PL)
- Canada (CA)
- Russia (RU)
- Australia (AU)

External debt data

First, a screening of the availability of external debt data was performed, which is defined by the IMF as *the outstanding amount of those liabilities that require payments of principal and or interest by the debtor at some point in the future and that are owned to nonresidents by residents of the economy* (IMF, 2014). The external debt statistics are measured and monitored by several international agencies worldwide, the two main databases publicly available are the World Bank Quarterly External Debt Statistics (QEDS)[17] and the Joint External Debt Hub (JEDH)[18].

The QEDS has the goal of facilitating the comparison and analysis of the external debt, providing a database initially developed by the IMF in conjunction with the World Bank, and now maintained by the latter. It contains external debt statistics for the countries that subscribe to the IMF's Special Data Dissemination Standard (SDDS) and also the ones participating in the IMF's General Data Dissemination System (GDDS), gathering the data that is published individually by each country (IMF, 2020; World Bank, 2021).

The JEDH was developed by the Bank for International Settlements (BIS), the IMF, the Organization for Economic Cooperation and Development (OECD), and the World Bank, gathering the external debt data and foreign assets from international creditors/markets, such as international reserves and portfolio investment assets. The major source of national data on external debt displayed in JEDH datasets comes from the QEDS, for this reason, the latter was selected for building the cross-country whom-to-whom matrix.

Therefore, the gross external debt data for the selected nineteen countries from 2008 to 2020 were extracted from QEDS, with the exception of China, for which the information is available from 2015 to 2020. The institutional sectors included in the QEDS are the general government, central bank, deposit-taking corporations (excluding central bank), direct investment, and other sectors.

For Australia, Brazil, India, and the Netherlands, an additional breakdown is available with the following categories: non-financial corporations, households and non-profit institutions serving households, and other financial corporations.

Domestic debt data

The most conventionally used source for obtaining domestic debt information of an economy is the System of National Accounts (SNA), which provides the total debt held disaggregated into institutional sectors, particularly, the balance sheets. They present total assets and total liabilities held/issued by resident institutional sectors (disaggregated) *vis-à-vis* non-residents (aggregated).

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[17] QEDS database is available at: https://www.worldbank.org/en/programs/debt-statistics/qeds#cross-country

[18] JEDH database is available at: http://www.jedh.org/data.html

Therefore, from SNA balance sheets, the information on how indebted each resident institutional sector is available, however, there is no information concerning the counterpart (for example, who issues the asset, whether the issuer is resident or not, etc.). Considering that QEDS provides the total debt held by residents (disaggregated into institutional sectors) *vis-à-vis* non-residents, a simple subtraction between the figures from the financial balance sheet and the external debt would result in the split between external and domestic debt. The problem arising from this simple subtraction is that the sectoral breakdown is different between the two data sources, as presented in

Table 3.8.

Table 3.8 | Sectoral breakdown of SNA and World Bank

External debt – World Bank	Financial balance sheets - SNA
General government	General government
Central Bank	Households and NPISHs
Deposit-taking corporations (other than CB)	Financial corporations
Direct investments	Non-financial corporations
Other sectors	

Therefore, linkages between both approaches must be conducted in order to obtain the split between domestic and external debt. For this purpose, the breakdown defined by the SNA is the one selected mainly because this is the breakdown of the data displayed in EXIOBASE. Moreover, it presents more detailed information compared to the breakdown available in the World Bank data, where different institutional sectors are put together (namely for direct investments and other sectors). The correspondences between the institutional sectors were conducted as presented in Table 3.9.

Table 3.9 | Allocation method for domestic and external debt

Institutional sectors from SNA	Sectors from QEDS
General government	= General government
Households and NPISHs	= 0
Financial corporations	= Central Bank + Deposit-taking corporations + $\mu \cdot$ Direct Investment + $\varphi \cdot$ Other sectors
Non-financial corporations	= $(1-\mu) \cdot$ Direct Investments + $(1-\varphi) \cdot$ Other sectors
Total economy	= Gross external debt

The general government is presented in both QEDS and SNA sectoral breakdown, being kept as it is in the allocation. The households and non-profit institutions serving the households sector are set to zero for external debt and fully allocated to domestic debt. This is justified by the fact that households are not significant loan takers in a cross-country perspective.

The financial corporations' sector is the sum of the 'central bank', the 'deposit-taking corporations', a percentage of the 'direct investment' (μ) and a percentage of 'other sectors'

(φ). The non-financial corporations' sector is the remaining percentage of the 'direct investments' $(1-\mu)$ and the 'other sectors' $(1-\varphi)$.

The challenge is to determine the shares represented by the Greek letters μ and φ. The OECD statistics publishes the weight of the financial and insurance sectors in the total Foreign Direct Investment (FDI), inward and outward. This weight varies through the countries, for example, in Luxembourg, the financial and insurance sector represents around 90% of total FDI, while it represents around 25% in France. Therefore, the share of 'direct investment' corresponding to the FCs (μ) is taken from financial FDI and the share of FCs is obtained residually $(1-\mu)$.

The percentage of 'other sectors' corresponding to the FCs (φ) and NFCs $(1-\varphi)$ are taken from their proportions of total debt held by FCs and NFCs, taken from the SNA financial balance sheets of each country.

For example, for France, in 2020, the amount of external debt represented by debt instruments was 7,394,750 million dollars (converted to 6,458,297 million euros), according to the QEDS data. This amount was held by the central bank (6%), deposit-taking corporations (50%), direct investment (7%), general government (25%), and other sectors (13%). Total liabilities represented by debt instruments in SNA were 24,992,565 million euros in the same year, held by non-financial corporations (20%), financial corporations (58%), general government (15%) and households and non-profit institutions serving households (7%).

The percentage of financial services in relation to total inward FDI of France in 2020 was 25.1%, meaning that financial services (banks, insurance companies, etc.) represented 25.1% of total foreign direct investment, which is the value of μ for France, 2020. The percentage of financial corporations in relation to 'other investment' (φ) is obtained from their shares on the liabilities from SNA, i.e., 58% divided by the sum of 58% and 20%, or 74%. The example of France, 2020, is presented in Figure 3.8.

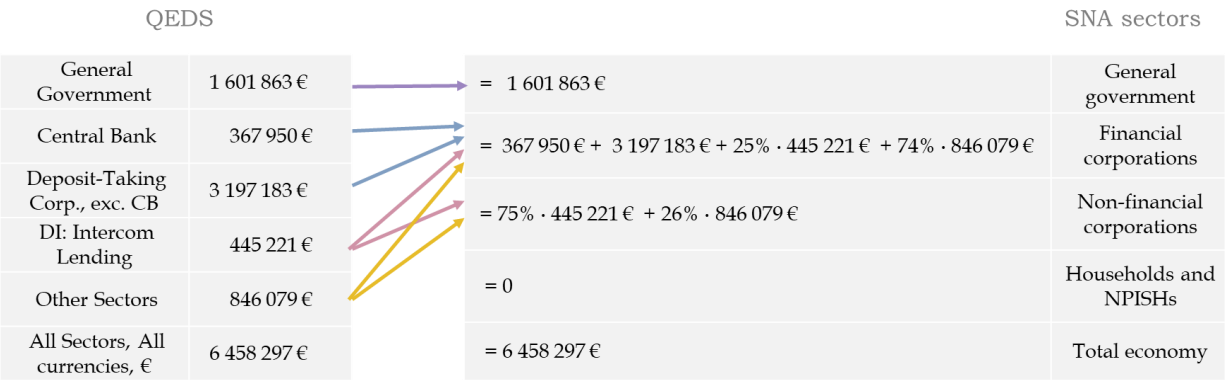


Figure 3.8 | Example of the allocation procedure for adapting the sectoral breakdown between QEDS and SNA

Once the allocation was conducted, the subtractions between total debt and external debt was made to obtain the split between external and domestic debt. The procedure previously described was applied for all the countries from 2008 to 2020. Table 3.10 is an example of the results for France.

Table 3.10 | Split between domestic and external debt for France, from 2015 to 2020

SNA in MEUR	2015	2016	2017	2018	2019	2020
Total economy	18 614 902 €	19 413 538 €	20 403 057 €	21 233 732 €	22 397 855 €	24 992 565 €
NFC	3 919 905 €	4 138 952 €	4 369 400 €	4 599 423 €	4 673 869 €	4 980 231 €
FC	10 287 913 €	10 754 409 €	11 347 267 €	11 840 395 €	12 711 067 €	14 463 208 €
GG	2 910 169 €	2 993 718 €	3 062 829 €	3 123 152 €	3 252 319 €	3 701 898 €
HH & NPISHs	1 496 915 €	1 526 457 €	1 623 562 €	1 670 763 €	1 730 502 €	1 847 227 €

External debt in MEUR	2015	2016	2017	2018	2019	2020
Total economy	4 598 231 €	4 730 940 €	4 792 885 €	5 090 901 €	5 461 470 €	6 458 297 €
NFC	495 791 €	530 623 €	549 981 €	495 790 €	511 248 €	550 185 €
FC	2 773 083 €	2 885 626 €	2 976 393 €	3 334 494 €	3 599 720 €	4 306 249 €
GG	1 329 357 €	1 314 691 €	1 266 511 €	1 260 618 €	1 350 503 €	1 601 863 €
HH & NPISHs	- €	- €	- €	- €	- €	- €

Domestic debt in MEUR	2015	2016	2017	2018	2019	2020
Total economy	14 016 671 €	14 682 598 €	15 610 172 €	16 142 831 €	16 936 385 €	18 534 268 €
NFC	3 424 114 €	3 608 329 €	3 819 419 €	4 103 633 €	4 162 621 €	4 430 046 €
FC	7 514 830 €	7 868 783 €	8 370 874 €	8 505 901 €	9 111 347 €	10 156 959 €
GG	1 580 812 €	1 679 027 €	1 796 318 €	1 862 534 €	1 901 816 €	2 100 035 €
HH & NPISHs	1 496 915 €	1 526 457 €	1 623 562 €	1 670 763 €	1 730 502 €	1 847 227 €

The last step of the data collection was to get the geographical breakdown of external debt between countries. The goal was to know the countries that hold a specific country's external debt, which is undisclosed information mainly for geopolitical reasons.

In order to estimate the geographical breakdown of external debt countries, the CPIS was used as the main reference because it presents the portfolio investment assets of non-resident issuers, disaggregated by country. CPIS provides the information concerning portfolio investment in form of total debt securities, and equity and investment fund shares. Debt securities represent a debt instrument and for this reason, the geographic breakdown of total debt securities was selected for applying the shares of debt, as presented in Table 3.11.

In the table, the lines represent the liability part, with the counterpart country represented in the columns. For example, reading the "FR" line and the "DE" column, means that Germany represents 15% of France's total liability. The column "Rest of the World" (RoW) is the difference between the total and the sum of the 19 selected countries.

Table 3.11 | Geographical breakdown allocation, 2020

2020	Investment from:																				
Investment in:	AU	BE	BR	CA	CN	FR	DE	IN	IE	IT	JP	LU	NL	PL	RU	ES	CH	GB	US	ROW	Total
AU		1%	0%	1%	5%	4%	6%	0%	3%	1%	20%	4%	1%	0%	0%	0%	2%	4%	20%	26%	100%
BE	0%		0%	0%	0%	18%	19%	0%	7%	4%	7%	8%	11%	0%	0%	1%	1%	2%	2%	18%	100%
BR	0%	0%		2%	0%	2%	2%	0%	4%	1%	3%	11%	4%	0%	0%	0%	2%	10%	19%	39%	100%
CA	2%	1%	0%		2%	2%	5%	0%	3%	0%	5%	4%	1%	0%	0%	0%	3%	4%	43%	24%	100%
CN	1%	0%	0%	0%	44%	1%	1%	0%	4%	0%	4%	6%	1%	0%	0%	0%	1%	2%	7%	26%	100%
FR	0%	3%	0%	0%	1%		15%	0%	8%	5%	9%	12%	7%	0%	0%	1%	2%	5%	8%	24%	100%
DE	1%	1%	0%	0%	1%	7%		0%	5%	3%	5%	10%	10%	0%	0%	1%	2%	5%	5%	42%	100%
IN	0%	0%	0%	2%	4%	1%	3%		2%	0%	6%	13%	1%	0%	0%	0%	1%	5%	18%	44%	100%
IE	0%	3%	0%	1%	0%	9%	12%	0%		4%	5%	8%	4%	0%	3%	2%	2%	12%	13%	23%	100%
IT	0%	2%	0%	0%	0%	17%	11%	0%	7%		7%	13%	1%	0%	0%	13%	1%	3%	4%	20%	100%
JP	2%	0%	0%	1%	5%	8%	2%	0%	4%	1%		5%	1%	0%	0%	1%	2%	6%	21%	42%	100%
LU	1%	5%	0%	1%	7%	21%	13%	0%	6%	3%	4%		3%	0%	2%	1%	5%	6%	9%	12%	100%
NL	1%	5%	0%	0%	1%	14%	17%	0%	6%	4%	6%	9%		0%	0%	3%	3%	4%	12%	16%	100%
PL	0%	4%	0%	2%	0%	8%	22%	0%	5%	3%	12%	8%	6%		0%	0%	3%	3%	7%	16%	100%
RU	0%	0%	0%	1%	0%	1%	5%	0%	25%	2%	2%	15%	4%	0%		0%	2%	7%	23%	14%	100%
ES	0%	2%	0%	0%	0%	18%	14%	0%	6%	13%	7%	8%	4%	0%	0%		1%	2%	5%	20%	100%
CH	1%	0%	0%	1%	1%	5%	4%	0%	11%	1%	4%	13%	3%	0%	0%	1%		9%	21%	23%	100%
GB	1%	1%	0%	1%	1%	7%	6%	0%	24%	1%	5%	11%	2%	0%	1%	1%	2%		18%	18%	100%
US	1%	0%	0%	3%	2%	3%	3%	0%	7%	1%	13%	7%	2%	0%	0%	0%	2%	5%		50%	100%
ROW	1%	1%	0%	1%	3%	6%	7%	0%	7%	2%	8%	8%	3%	0%	0%	1%	2%	4%	10%	33%	100%

3.6 Conclusions

The methodology developed here combines the key elements from a dynamic input-output model and the stock-flow consistent model. Input-output modelling is used to calculate the monetary distribution and re-distribution, while the stock-flow consistent model ensures that the economic balances are indeed consistent as each monetary flow is recorded as an income for someone and an outcome for someone else. Moreover, the SFC framework allows the linkage between the distribution rounds in a consistent way, where the changes in stocks are accounted for as a result of the changes in flows (linking financial and non-financial sides of the economy). Figure 3.9 shows an illustrative representation of the distribution model.

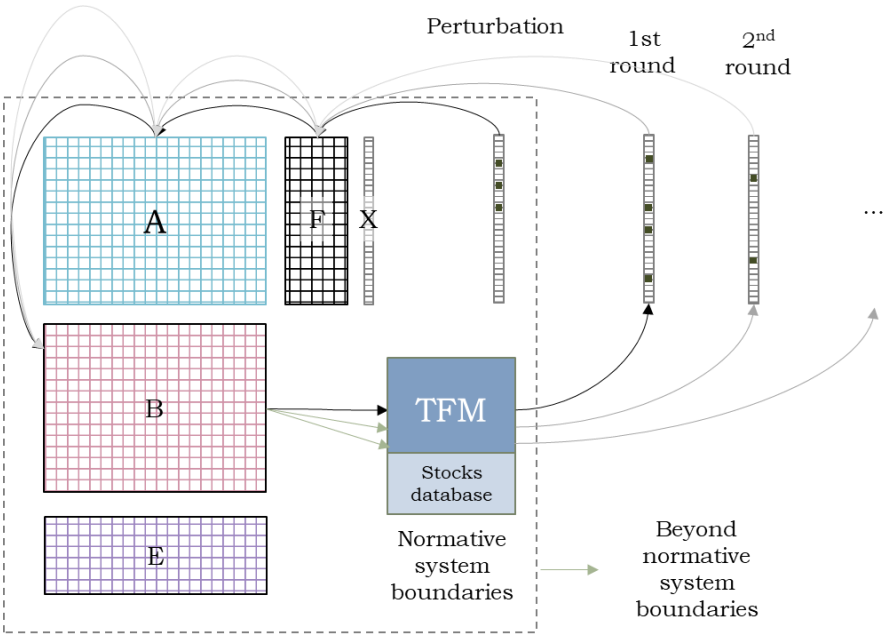


Figure 3.9 | Monetary distribution illustrative representation

Matrix A represents the technological coefficient matrix, with the inputs required per unit of output of each activity. Matrix B and E are the extensions of the IO table, where B presents the coefficients of value-added elements and E shows the coefficients of substance emissions per unit of output. F represents the final demand elements, and X the total outputs, which are equal to total inputs for the monetary version. All of these matrices are obtained from EXIOBASE.

The economic perturbation represents the functional unit of the study (Section 3.2.2) and triggers the change in outputs, which are obtained by the Leontief's inverse (see Section 3.3.4). Then, the changes in environmental elements are obtained, and the new value-added matrix is calculated. The value-added changes are accounted for in a transaction-flow matrix (TFM), which is composed of two sides: changes in flows and changes in stocks. For the latter, the stocks database (see Section 3.5) is integrated, from where all information concerning marginal debt is taken (from-whom-to-whom matrix).

The resulting changes in stocks of households trigger the induced consumption, which is considered the second round of a period distribution. One period in this methodology represents one year on average, however, it is possible to adapt it to each case.

Second Part

4

Method applied to the case study: method transcription

This chapter transcribes the method presented in Chapter 3 to a case study in the construction sector. In this thesis, the French Recovery Plan was studied, particularly the part of the budget dedicated to increasing thermal retrofitting works in France. Three versions of the case study are assessed here, with different levels of detail of the perturbation. The first version, called "total budget, simplified version" includes both residential and public buildings; however, the perturbation affects the construction works, without detailing which types of works are conducted. The second version, called "only residential, detailed version", studies only the residential buildings. The marginal number of thermal retrofitting works by type of work is estimated by using an econometric model. The third version, called "only residential, simplified", only considers residential buildings as in the previous version; however, it simplifies the perturbation by assuming that the only affected activity is the "construction works", as considered in "total budget, simplified version".

The method is presented step-by-step to illustrate how to apply the theoretical framework presented in Chapter 3, for the three versions.

4.1 Case study description and system boundaries

The COVID-19 pandemic's effects have affected worldwide economic activity in many ways. For this reason, several measures to help rebuild the economies have been implemented globally. In Europe, the European Union has launched the EU's long-term budget, which is associated with the NextGenerationEU (NGEU) program focused on rebuilding Europe post-COVID. In France, for example, the Government presented in 2020 the French Recovery Plan, with an extra 100 billion euros to support economic activity and job creation. The plan is based on three pillars: green transition, competitiveness, social and territorial cohesion, with a

budget of 5.2 billion euros dedicated to increasing energy efficiency in residential and tertiary built stock, particularly to foster thermal retrofitting on a national scale.

According to the detailed report from the French National Congress, the budget from the French Recovery Plan will be used as follows:

- 2.0 billion euros in financial aid to purchase efficient heating and domestic hot water equipment and insulating materials for residential buildings (mainly through MaPrimeRénov'[19])
- 0.2 billion euros for private enterprises
- 3.2 billion euros in investment in thermal retrofitting measures in public buildings (schools, hospitals, social housing, etc.)

Therefore, the goal of the case study is to assess the environmental and economic impacts associated with the French recovery plan, in particular, the incentives (financial aid) for conducting a massive thermal retrofitting in public and residential buildings. The functional unit of the study is thus to conduct a massive retrofitting in France fostered by the fiscal incentives: 2 billion euros for residential buildings and 3.2 billion euros for public buildings.

This budget is the money that is inputted into the French economy, coming from outside France dedicated to finance the Recovery Plan. The money is used to purchase efficient heating and domestic hot water equipment and insulating materials. However, there is no information on what types of thermal retrofits are specifically financed by the plan. For this reason, two options were considered in this thesis: a simplified and a detailed perturbation. The first one considers that all the money is received by the "construction works" activities (as listed in Appendix 2).

"Construction works (45)" is one of the activities that are included in EXIOBASE, which are based on NACE coding system. NACE provides a common ground on the classification of economic activities and stands for "Statistical Classification of Economic Activities in the European Community", the French term "*Nomenclature statistique des Activités économiques dans la Communauté Européenne*". The NACE code 45 includes "general construction and special trade construction for buildings and civil engineering, building installation and building completion. It includes new work, repair, additions and alterations, the erection of pre-fabricated buildings or structures on the site and also constructions of a temporary nature" (Eurostat, 2020).

The detailed version estimates the amounts of thermal retrofits based on a French econometric model, developed by the French Environmental Agency (ADEME), called MENFIS (for "Modèle ENergie FIScalité des logements" in French)(Nauleau and Saussay,

[19] MaPrimeRénov' is a French Program launched in January 2020 to grant financial aids and foster thermal retrofitting in French residential built stock

2019). MENFIS is a prospective model that simulates on a yearly basis the impact of incentive policies aimed at reducing energy consumption in residential buildings in France. It includes a thermal module that provides changes in energy consumption according to the evolution of the number of retrofitting works.

Discussion on system boundaries

The normative system boundaries of the thermal retrofitting works for the two versions are presented in Figure 4.1. The supply chain includes the products and services needed to produce the outputs listed in the "production" phase. This means that the raw materials are included as well as services (telecommunication, for example) and wastes treatment (incineration, recycling, etc.). The production phase is included through the production modelled in EXIOBASE, as already mentioned in the previous paragraphs. Finally, the use phase only includes the energy consumption.

The main differences between the two versions, as aforementioned and highlighted in Figure 4.1, are the level of detail for the production of thermal retrofitting products and the buildings typology affected by the thermal retrofitting policy.

The expanded system boundaries are included in the second round of each period, when the induced consumption takes place. There is no difference between the versions with regard to the boundaries of the second-order effects, for this reason, only normative system boundaries are illustrated in Figure 4.1.

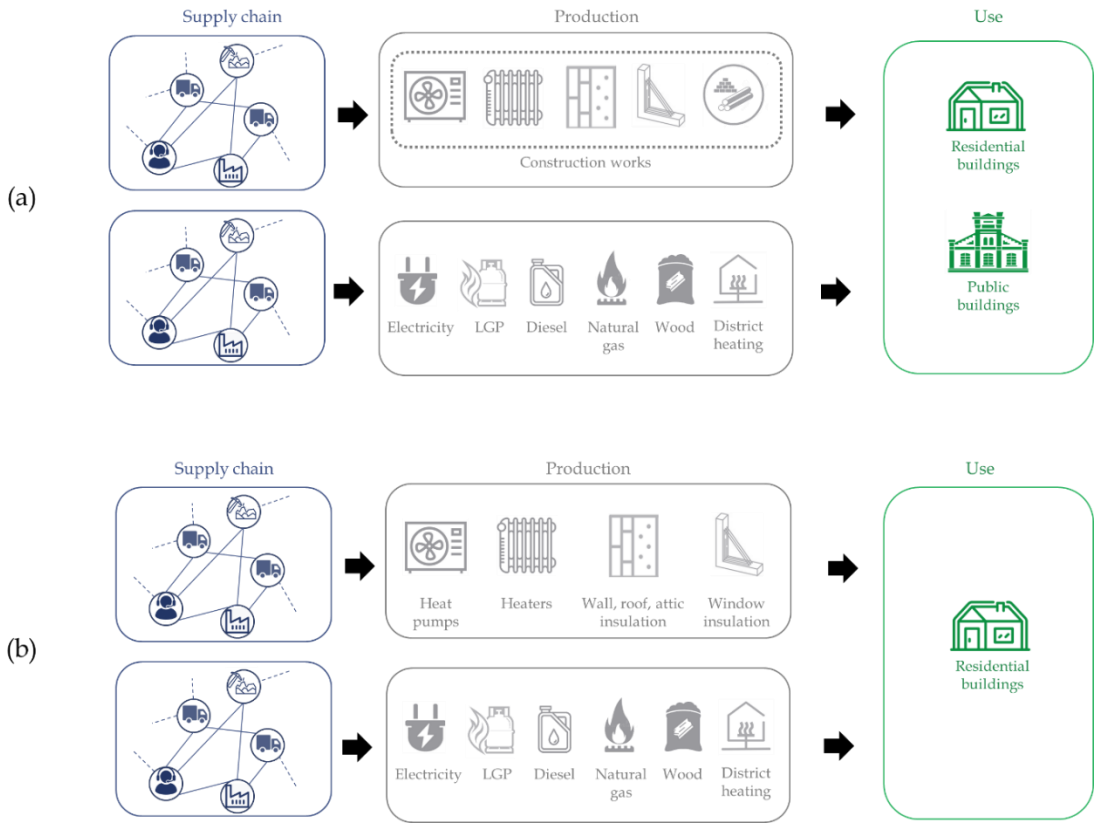


Figure 4.1 | System boundaries (a) simplified version and (b) detailed version

4.2 Defining the studied exogenous perturbation

4.2.1 Total budget, simplified version

4.2.1.1 Thermal retrofitting works

The total French Recovery Plan budget dedicated to conducting thermal retrofits represents the exogenous perturbation in the simplified version and it affects the EXIOBASE activity named "**construction works"** in France. The latter includes the activities of the construction sector, such as general construction and special trade construction for buildings and civil engineering, building installation and building completion (European Commission, 2005). Examples of EXIOBASE activities having significant inputs for the 'construction work' in France, 2020, are:

- Construction works
- Other business services
- Fabricated metal products, except machinery and equipment
- Cement, lime and plaster
- Wholesale trade and commission trade services, except of motor vehicles and motorcycles
- Electrical machinery and apparatus not elsewhere classified (n.e.c.)
- Rubber and plastic products
- Wood and products of wood and cork (except furniture); articles of straw and plaiting materials
- Financial intermediation services, except insurance and pension funding services
- Supporting and auxiliary transport services; travel agency services
- Renting services of machinery and equipment without operator and of personal and household goods

In the simplified version, the initial perturbation vector is thus 5.2 billion euros in the French "construction works" row and zero for all other activities. This initial exogenous perturbation occurs at the beginning of the first period (represented by the red arrow in Figure 4.2). The 5.2 billion euros come from the general government (GG) (3.2 billion euros) and households (HH) (2.0 billion euros). However, the households are disaggregated into three income level groups. Therefore, since the perturbation must be stock-flow consistent, the perturbation must be also disaggregated.

Disaggregating households

The three income levels used by EXIOBASE come from the International Labour Organization (ILO) classification, as presented in Table 4.1.

Table 4.1 | Household income levels description (adapted from (ILO, 2015))

Broad skill levels	ISCO-08[20]	ISCO-88
Levels 3 and 4 (high-skilled)	Managers, professionals, technicians and associated professionals	Legislators, senior officials and managers, professionals, technicians and associated professionals
Level 2 (medium-skilled)	Clerical support workers, service and sales workers, skilled agricultural, forestry and fishery workers, craft and related trades workers, plant and machine operators, and assemblers	Clerks, service workers, shop and market sales workers, skilled agricultural and fishery workers, craft and trade workers, plant and machine operators
Level 1 (low-skilled)	Elementary occupations	Elementary occupations

In France, the distribution of employed people by socio-economic category is presented in Table 4.2. The percentages were obtained from the INSEE report on international labour data (INSEE, 2018), which uses as a source the Eurostat Labour survey data from 2015. The association between the classification of ILO and the employment distribution in France is also presented in Table 4.2.

Table 4.2 | Distribution of employed people by socio-economic category (adapted from (INSEE, 2018))

Occupations	Percentage in France	ILO Classification
Executive managers	8%	High-skilled
Intellectual and scientific professions	21%	High-skilled
Intermediate salaried professions	19%	Medium-skilled
Small entrepreneurs	8%	Medium-skilled
Qualified employees	14%	Medium-skilled
Qualified salaried workers	13%	Medium-skilled
Low-skilled employees	17%	Low-skilled
All employed people (in thousands)	26 536	

As explained in Section 4.1, Recovery Plan's major tool for encouraging thermal retrofitting works in residential buildings is increasing the scope of MaPrimeRénov' (MPR) primes. It is worth mentioning that MPR was launched in 2020, and was limited only to lower-income groups. One way of understanding the marginal change in the number of thermal retrofitting works for each household's income level is to study the changes in the MPR values

[20] Classification from the International Standard Classification of Occupations (ISCO). ISCO-88 was approved by the ILO Governing Body in 1988, while ISCO-08 was endorsed by the Governing Body of the ILO in March 2008 (ILO, 2019).

of primes in 2020 and 2021, knowing that the Recovery Plan allowed extending the scope of MPR to medium- and high-income levels. These two income groups were covered before by the tax credit measure called CITE (for *Credit d'Impôt pour la Transation Energétique*, in French), which has been extinguished since the creation of MPR. The table comparing the financial aids before and after the Recovery Plan is presented in Appendix 5.

Therefore, considering the changes in aid received by each income group due to the Recovery Plan, the estimations are the following: 24% for low-skilled, 58% for medium-skilled and 18% for high-skilled households, therefore the 2 billion perturbation is divided into: 0.474 billion euros for/from low-skilled, 1.169 billion euros for/from medium-skilled and 0.357 billion euros for/from high-skilled households.

4.2.1.2 Energy savings

The exogenous perturbations that occur in the beginning of the other periods are the energy saved (orange arrows) and the money re-spent from monetary distribution (grey arrows).

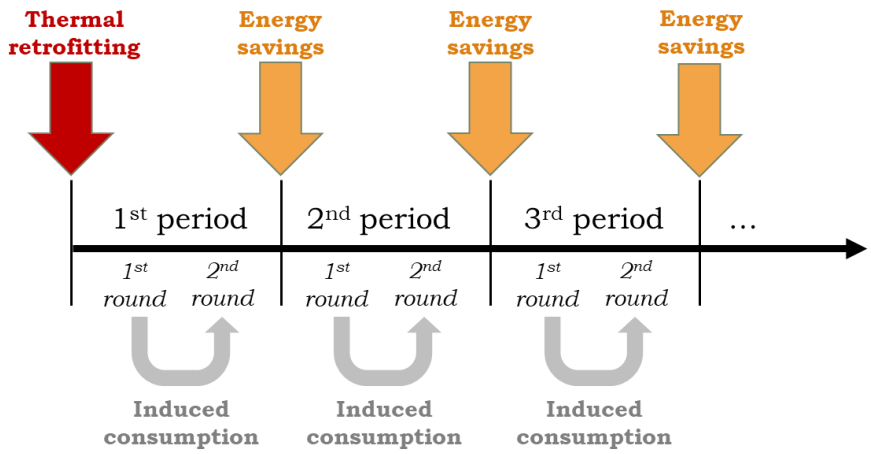


Figure 4.2 | Representation of exogenous perturbations

The energy saved in this simplified version is estimated from the literature. For that, three options are described here: (A) to vary the payback of the investment from 10 to 30 years, a common practice on energy efficiency studies; (B) to use the surveys on the money saved after carrying out thermal retrofitting works in their homes, presented in terms of return on investment by Blaise & Glachant (2019); and (C) to use the estimation made by the Government of 139 GWh of primary energy saved for 989 million euros invested in thermal renovation in public administration buildings (140.5 GWh/billion euro)(Direction de l'Immobilier de L'Etat, 2019).

The first two options are based on the principle that thermal retrofitting is an energy efficiency measure and the savings provide a return on investment. The surveys analyzed by Blaise & Glachant (2019) showed a return on investment of 120 years, as the authors found that the households save 8.39 euros for 1,000 euros invested in thermal retrofitting measures.

One of the reasons for these results is the inclusion of this average of less efficient measures, which have a cost and do not significantly save energy. Another point is the change in heating energy sources for lower emitting ones does not mean money savings, rather emission savings.

The estimations from the French government of 140.5 GWh primary energy saved per billion euros invested (option C) is based on experts' opinion and thermal modelling. They can be applied to residential buildings because the nature of the thermal retrofitting works, even if it is not the same, does not vary a lot from tertiary to residential buildings. In addition, estimates are provided in terms of primary energy saved (physical unit) and not money saved, unraveling issues associated with heating energy sources and their prices that would be hidden in monetary-saving intensities. Indeed, the heating sources of tertiary buildings are not the same as the ones for residential buildings, as presented in Table 4.3.

Table 4.3 | Shares of final energy consumption (physical unit shares) for heating, according to the typology of building in 2020 (CEREN, 2021a, 2021b)

Source	Residential buildings	Tertiary buildings
District heating	4%	8%
Diesel	13%	18%
Natural gas	43%	56%
LGP	1%	1%
Wood pellets	26%	1%
Electricity	13%	16%

The price of each energy source depends on the type and also on the contract to purchase the energy, for example, the price of diesel is not the same for households and for enterprises. The prices that are considered in this thesis are presented in Table 4.4.

Table 4.4: Average prices of different energy sources in 2019

Energy source	Average price in 2019 (€/kWh)	
	Households	Tertiary
District heating (2)	0.0746	0.0746
Diesel (1)	0.086	0.05
Natural gas (1)	0.086	0.04
LGP (1)	0.144	0.144
Wood pellets (3)	0.066	0.066
Electricity (1)	0.178	0.105
Average price of 1kWh (€)	*0.093*	*0.057*

Sources: (1) (SDES, 2020)**; (2)** (AMORCE, 2020)**; (3)**(ADEME, 2020)

The additional 2 billion euros for households to conduct thermal retrofitting works would cause a reduction of 281 GWh by year in energy consumption, in option C, while tertiary public buildings would save 450 GWh by year in primary energy. However, since the energy cost for tertiary public buildings is lower than for households (as presented in Table

4.4), the savings are less expressive than for households, as Table 4.5 shows. The conversion from primary to final energy is needed for obtaining monetary savings since data from Table 4.4 is provided in terms of final energy. The conversion is only applied in the electricity, as defined in the French Environmental Regulation (RE2020), with the factor 2.3 (Ministère de la Transition Ecologique, 2021, table 11), meaning that 2.3 kWh in primary energy are needed to provide 1 kWh of final energy. The results in terms of saved final energy are also presented in Table 4.5.

Table 4.5 | Energy savings of each solution for residential and tertiary buildings

	Residential	Tertiary
Investment (bi €)	2	3.2
Savings in energy bills – option A (mi €)	67	107
Savings in energy bills – option B (mi €)	17	27
Savings in energy bills – option C (mi €)	24	23
Primary energy saved (GWh) - SC1.C	281	450
Final energy saved (GWh) - SC1.C	259	408

The exogenous perturbation in EXIOBASE is obtained by multiplying the final energy saved by the shares and prices of each source. However, for electricity, the total value is disaggregated following the shares from French households demand for electricity, obtained from EXIOBASE, for 2020, as presented in Table 4.6.

Table 4.6 | EXIOBASE electricity final demand of households in France, 2020

EXIOBASE activity	**Final demand of households (MEUR)**	**Share**
Electricity by coal	1185	5.6%
Electricity by gas	1310	6.2%
Electricity by nuclear	15915	75.6%
Electricity by hydro	1857	8.8%
Electricity by wind	0	0.0%
Electricity by petroleum and other oil derivatives	233	1.1%
Electricity by biomass and waste	326	1.5%
Electricity by solar photovoltaic	0	0.0%
Electricity by solar thermal	0	0.0%
Electricity by tide, wave, ocean	12	0.1%
Electricity by Geothermal	0	0.0%
Electricity n.e.c.	225	1.1%
Transmission services of electricity	3207	15.2%
Distribution and trade services of electricity	12236	58.1%

Concerning the transmission services and the distribution and trade services of electricity, we considered that decreases in electricity demand will affect these services proportionally, with the shares presented in Table 4.6. Therefore, the affected activities as well

as the values of energy saved considered for each scenario of the simplified version are presented in Table 4.7.

Table 4.7 | Perturbation of energy savings from the second period and so on, simplified version (MEUR)

Final energy source	EXIOBASE activity	Option A	Option B	Option C
District heating	Steam and hot water supply services	-13.7	-3.5	-3.3
Diesel	Gas/Diesel Oil	-24.5	-6.2	-6.5
Natural gas	Distribution services of gaseous fuels through mains	-67.8	-17.1	-18.6
LGP	Liquefied Petroleum Gases (LPG)	-4.8	-1.2	-1.2
Wood pellets	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	-13.3	-3.4	-4.7
Electricity	Total electricity	-49.2	-12.4	-13.2
	Electricity by coal	-2.8	-0.7	-0.7
	Electricity by gas	-3.1	-0.8	-0.8
	Electricity by nuclear	-37.2	-9.4	-10.0
	Electricity by hydro	-4.3	-1.1	-1.2
	Electricity by wind	0.0	0.0	0.0
	Electricity by petroleum and other oil derivatives	-0.5	-0.1	-0.1
	Electricity by biomass and waste	-0.8	-0.2	-0.2
	Electricity by solar photovoltaic	0.0	0.0	0.0
	Electricity by solar thermal	0.0	0.0	0.0
	Electricity by tide, wave, ocean	0.0	0.0	0.0
	Electricity by Geothermal	0.0	0.0	0.0
	Electricity n.e.c.	-0.5	-0.1	-0.1
	Transmission services of electricity	-7.5	-1.9	-2.0
	Distribution and trade services of electricity	-28.6	-7.2	-7.7

Because the option C presents intermediate values when compared to the other two options, it is the selected scenario for the first calculations.

4.2.2 Only residential, detailed perturbation

MENFIS simulates the number of thermal retrofits, by typology, and the saved energy, by energy vector, based on the changes in fiscal incentives. The fiscal incentives included in MENFIS are:

- The tax credit scheme (CITE, formerly CIDD): income tax credits eligible for all households, regardless of their level of income
- The Zero Rate Loan (EcoPTZ): free-interest loans granted over 10 years for the retrofitting investment on dwellings built before 1990
- The direct subsidies to energy renovation, such as MaPrimeRenov'
- Reduced tax mechanisms such as reduced value-added tax (VAT)

- Carbon tax, also called climate-energy contribution (CCE), based on the polluter/payer principle

As mentioned in Section 4.1, the financial aids for residential retrofitting are mainly made through MaPrimeRénov provisions. The French Recovery plan enabled increasing the grants for purchasing specific equipment and for installing insulation (panels, windows), but the greatest change was to open up the grants to all households, regardless of their income level.

Considering that MENFIS also takes into account other types of financial aid that would take place unrelatedly to the Recovery Plan and influence the number of retrofitting works as well as other outcomes of the model, two simulations were conducted for 2021, knowing that the reference year is 2020. The first was to obtain a 'business-as-usual' (BAU) scenario, i.e., run the model without the changes triggered by the Recovery plan. The second simulation was conducted by increasing the MaPrimeRénov' grants to the new values facilitated by the Recovery Plan were conducted to obtain an increase in 2 billion euros of thermal retrofitting works.

4.2.2.1 Thermal retrofitting works

The outputs of MENFIS concerning the thermal retrofitting works are presented in Table 4.8. The third column presents the additional retrofitting works that are associated with the French Recovery Plan, in relation to the BAU retrofits that would occur without the increase in MaPromeRénov aids.

Table 4.8 | Outputs of MENFIS in terms of additional retrofitting works (number of new retrofitting works)

Thermal retrofitting works	Houses		Apartments		Total dwellings	
	BAU	Only Recovery Plan	BAU	Only Recovery Plan	BAU	Only Recovery Plan
Gas condensing boiler	83103	21200	131926	4370	215029	25570
Fuel condensing boiler	120487	55420	25009	11234	145496	66653
Heat pump air/air	149131	64832	50851	34304	199981	99136
Wood boiler	42036	-114	0	0	42036	-114
Fireplace Inserts	288608	188596	0	0	288608	188596
Heat pump air/water	16402	5623	13412	-4243	29814	1381
Windows	409031	41137	274266	2527	683296	43665
Wall Insulation	352024	183787	72182	89064	424205	272851
Roof/attic insulation	329886	149226	99049	80772	428935	229998

A first solution for representing these retrofitting works is to attribute directly to each one of them an existing product from the EXIOBASE list (presented in Appendix 2), which is based on the NACE classification.

Table 4.9 | Relationship between retrofitting works and EXIOBASE

Retrofitting work	Exiobase activity
Gas condensing boiler	Machinery and equipment n.e.c.
Fuel condensing boiler	Machinery and equipment n.e.c.
Heat pump air/air	Machinery and equipment n.e.c.
Wood boiler	Machinery and equipment n.e.c.
Fireplace Inserts	Machinery and equipment n.e.c.
Heat pump air/water	Machinery and equipment n.e.c.
Windows	Glazing - Glass and glass products Frame - Aluminium and aluminium products Rubber and plastic products Wood and products of wood and cork (except furniture)
Wall Insulation	Glass and glass products Other non-metallic mineral products Rubber and plastic products Wood and products of wood and cork (except furniture)
Roof/attic insulation	Glass and glass products Other non-metallic mineral products Rubber and plastic products Wood and products of wood and cork (except furniture)

The NACE code 29 covers the manufacture of machinery and equipment and is divided into seven sub-categories, of which the manufacture of electric and non-electric domestic appliances (NACE 29.71 and 29.72). All the boilers, the fireplace, and both types of heat pumps are included in this classification.

The replacement of windows (single-glazed by double or triple-glazed) is more challenging to associate directly with EXIOBASE activities because there is not a single category to cover this product in NACE. Therefore, a market research must be conducted to support the selection of the activities that are affected. For this purpose, the market shares from 2019 presented in the study conducted by the French joinery manufacturers association (UFME, 2020) were used as a reference in this thesis. According to the study, the market shares are the following: aluminium-framed 29.9%, wood-framed 8.5%, PVC 59.7%, and others 1.8%. The EXIOBASE activities that associated with the frames are thus:

- Aluminium and aluminium products (which includes the activity 28.12.10.50 for carpentry and joinery of metal)
- Rubber and plastic products (which comprises the activity 25.23.14.50 for plastic frames of windows)
- Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (which includes the activity 20.30.11.00 for wooden windows frames)

Similarly, walls, roof, and attic insulation have a diversity of sources of materials. Therefore, the market shares of the types of insulating materials must be applied. For this purpose, a confidential market study from CSTB was used in this thesis. Considering that the study is confidential, the values are not presented in this manuscript, rather we present the

aggregated percentages of the market participation of the main types of materials. Among them, glass wool and rock wool (more than half of the market), expanded and extruded polystyrene, polyurethane (more than 40%), and others (including bio-based materials, such as cork slab and wood wool) less than 10%. MENFIS distinguishes between the surface of wall and roof and attic insulation, which do not use the same materials, i.e. the shares of the materials are not the same for walls and roof/attic, and these shares were also obtained from the confidential report. The EXIOBASE activities are the following:

- Glass and glass products for glass wool, knowing that the NACE category 26.14 (a sub-category of glass and glass products) includes glass wool mats
- Other non-metallic mineral products: it is an activity that covers the manufacture of other non-metallic mineral products (NACE category 26.82), which includes the rock wool
- Rubber and plastic products, which is the most appropriate category for plastic primary products, even though the manufacture of plastics in primary forms (including EPS, XPS, PU) are included in the NACE category 24.16

The perturbation is therefore the multiplication of the number of each thermal retrofitting work from MENFIS simulation by their cost to households, knowing that the financial aids only cover one part of the cost of the retrofitting works. Table 4.10 presents the costs as considered by MENFIS, for the year 2021.

Table 4.10 | costs of retrofitting works to households

Thermal retrofitting works	Cost per work (€/work)	
	Houses	Apartments
Gas condensing boiler	4343	3475
Fuel condensing boiler	4343	3475
Heat pump air/air	7934	7934
Wood boiler	16513	16513
Fireplace Inserts	4638	4638
Heat pump air/water	10913	10913
Windows	7541	5634
Wall Insulation	9877	7203
Roof/attic insulation	5064	2522

In this case, the perturbation affects the following EXIOBASE activities: Machinery and equipment n.e.c., Glass and glass products, Aluminium and aluminium products, Rubber and plastic products, Wood and products of wood and cork (except furniture), other non-metallic mineral products. The economic perturbation is described in Table 4.11.

Table 4.11 | Perturbation of retrofitting works in Billion euros

Retrofitting work/ EXIOBASE activity	Gas condensing boiler	Fuel condensing boiler	Heat pump air/air	Wood boiler	Fireplace Inserts	Heat pump air/water	Windows	Wall Insulation	Roof/attic insulation
Machinery and equipment n.e.c.	0.107	0.280	0.787	-0.002	0.875	0.015	-	-	-
Glass and glass products	-	-	-	-	-	-	0.234	0.765	0.299
Aluminium and aluminium products	-	-	-	-	-	-	0.031	-	-
Rubber and plastic products	-	-	-	-	-	-	0.030	1.158	0.452
Wood and products of wood and cork (except furniture)	-	-	-	-	-	-	0.029	0.107	0.042
Other non-metallic mineral products	-	-	-	-	-	-	-	0.427	0.167
Total (BEUR)	0.107	0.280	0.787	-0.002	0.875	0.015	0.324	2.457	0.959

Disaggregating households

The total amount spent in each retrofitting work is easily obtainable from MENFIS, as presented in the previous tables, however, this information needs to be disaggregated from the demand side so that the whom-to-whom matrix is calculated. MENFIS provides the amounts of thermal retrofitting works conducted by households disaggregated by income quintile, as presented in Table 4.12.

Table 4.12 | Retrofitting works by income quintile, from MENFIS

Retrofitting works	1st Quintile		2nd Quintile		3rd Quintile		4th Quintile		5th Quintile	
	BAU	Recovery Plan	BAU	Recovery Plan	BAU	Recovery Plan	BAU	Recovery Plan	BAU	Recovery Plan
Gas condensing boiler	40520	432	40390	428	40620	3125	45377	10130	48122	11454
Fuel condensing boiler	17230	7060	19960	9255	27658	13176	38046	18050	42602	19112
Heat pump air/air	21718	14144	22039	15023	32475	18960	52638	24301	71112	26709
Wood boiler	7679	-17	8530	-18	9327	-23	9389	-35	7111	-21
Fireplace Inserts	32670	17566	40853	23020	50005	39224	78745	53016	86336	55770
Heat pump air/water	4089	-1154	3909	-1098	4290	-628	8342	1829	9185	2432
Windows	126194	3486	127368	5324	132607	12414	145909	10703	151218	11737
Wall Insulation	51208	42787	57863	45888	69289	38852	114836	71204	131010	74120
Roof/attic insulation	53458	31308	59169	32228	72065	46097	111823	58225	132420	62141

Therefore, the perturbation was disaggregated by using the percentages by quintile (obtainable from Table 4.12) and associating to each quintile an income group as presented in Table 4.2 and in Figure 4.3. Note that the high-skilled households are associated with the 5th quintile, even if the latter correspond to 20% of population and their percentage in France is 29%. This approximation was made since there is no information available on deciles from MENFIS.

ILO Classification	Occupations	Percentage in France	
High-skilled	Executive managers	8%	5th quintile
High-skilled	Intellectual and scientific professions	21%	
Medium-skilled	Intermediate salaried professions	19%	2nd, 3rd and 4th quintiles
Medium-skilled	Small entrepreneurs	8%	
Medium-skilled	Qualified employees	14%	
Medium-skilled	Qualified salaried workers	13%	
Low-skilled	Low-skilled employees	17%	1st quintile
	All employed people (in thousands)	26 536	

Figure 4.3 | Relationship between income quintiles and ILO income groups

The total of retrofitting works disaggregated by income group, as well as the total money spent by each group on each thermal retrofitting work (and the total) is presented in Table 4.13.

Table 4.13 | Number of thermal retrofitting works per income group

Retrofitting works	Low-skilled		Medium-skilled		High-skilled	
	Number of works	Expenditure (BEUR)	Number of works	Expenditure (BEUR)	Number of works	Expenditure (BEUR)
Gas condensing boiler	432	0.001	13683	0.057	11454	0.049
Fuel condensing boiler	7060	0.029	40481	0.170	19112	0.081
Heat pump air/air	14144	0.112	58283	0.462	26709	0.212
Wood boiler	-17	0.000	-76	-0.001	-21	0.000
Fireplace Inserts	17566	0.081	115260	0.535	55770	0.259
Heat pump air/water	-1154	-0.013	103	0.001	2432	0.027
Windows	3486	0.025	28441	0.211	11737	0.088
Wall Insulation	42787	0.367	155944	1.400	74120	0.690
Roof/attic insulation	31308	0.110	136550	0.569	62141	0.280
Total	***115612***	***0.713***	***548669***	***3.404***	***263454***	***1.685***

Therefore, the perturbation presented in Table 4.11 is paid from HH income groups following the totals from Table 4.13.

4.2.2.2 Energy savings

The energy savings in this detailed approach are obtained from MENFIS, as presented in Table 4.14, the outputs concerning the changes in demand for heating energy are provided in terawatt-hours (TWh), by energy source: natural gas, diesel, electricity, wood pellets and district heat. The results of MENFIS simulations are presented in Table 4.14.

Table 4.14 | Outputs of MENFIS in terms of changes in energy demand (TWh)

Energy source	BAU	Only recovery Plan
Natural gas	103	-0.9
Diesel	48	-1.3
Electricity	34	-0.1
Wood pellets	65	0.8
District heating	14	-0.1
Total	264	-1.7

The average prices from Table 4.4 and the electricity shares of households' final demand from Table 4.6 were applied to these changes obtained by MENFIS. The results in terms of energy savings (physical and monetary) are presented in Table 4.15. Therefore, the perturbation concerning the energy savings applies to the activities as presented in Table 4.15, all other rows of the perturbation vector are zero.

Table 4.15 | Perturbation on energy savings, from the second round and so on, detailed approach

Energy source	EXIOBASE activity	Energy savings (TWh)	Energy savings (MEUR)
District heating	Steam and hot water supply services	- 0.149	- 11.099
Diesel	Gas/Diesel Oil	- 1.333	- 114.610
Natural gas	Distribution services of gaseous fuels through mains	- 0.861	- 74.049
Wood chips	Wood and products of wood and cork	0.772	50.959
Electricity	Total electricity	- 0.142	- 25.321
	Electricity by coal	-	- 1.425
	Electricity by gas	-	- 1.575
	Electricity by nuclear	-	- 19.132
	Electricity by hydro	-	- 2.232
	Electricity by wind	-	-
	Electricity by petroleum and other oil derivatives	-	- 0.280
	Electricity by biomass and waste	-	- 0.392
	Electricity by solar photovoltaic	-	-
	Electricity by solar thermal	-	-
	Electricity by tide, wave, ocean	-	- 0.014
	Electricity by Geothermal	-	-
	Electricity n.e.c.	-	- 0.270
	Transmission services of electricity	-	- 3.855
	Distribution and trade services of electricity	-	-14.710
	Total	***1.713***	***218.0***

The disaggregation of energy savings by income group follows the proportions of the expenditures of each group. This means that low-skilled households save 12% of €218.0 million, or €28 million, medium-skilled households save 59% of total, or €128 million, and high-skilled households save 29% of total, or €63 million.

4.2.3 Only residential, simplified version

For comparing the simplified and detailed approaches for building an exogenous perturbation, a third scenario was built: "only residential, simplified". The idea is to use the same assumptions used for building the thermal retrofitting works and energy savings perturbation in the detailed version, but only the part of residential buildings.

4.2.3.1 Thermal retrofitting works

For comparison purposes, the exogenous perturbation has the same magnitude as the detailed version, i.e., €5.8 billion. The assumption is that the money received by households to conduct thermal retrofitting services does not cover for their whole expenditure. As estimated in Section 4.2.1.1, low-skilled HHs receive 24%, medium-skilled HHs receive 58% and high-skilled HHs receive 18% of total budget for residential buildings. In this version, these proportions are kept the same, i.e., low-skilled HHs spend €1.4 billion, medium-skilled HHs spend €3.4 billion and high-skilled HHs spend €1.0 billion in the Exiobase activity called "construction works".

4.2.3.2 Energy savings

For energy savings, the assumptions are the same as the ones presented for the simplified version of total budget (see Section 4.2.1.2). The selected option for estimating the energy savings in function of the money invested was that 140.5 GWh of primary energy are saved per billion euro invested on thermal retrofitting works. This means that, for 5.8 billion, 816 GWh are saved in primary energy, or 752 GWh in final energy. This results in a reduction of around €0.070 billion saved by households per year.

4.3 Defining the pertinent transactions and institutional sectors

In both simplified and detailed versions, the total expenditure used to purchase efficient equipment and insulating material are accounted as use of 'gross fixed capital formation' for households, disaggregated by income level, and for the general government and, in counterpart, they are a resource for non-financial corporations (NFC). This extra money comes in one part from the European Union (40%), accounted as "other current transactions" and the other part comes from loans taken out by French Government, coming from other institutional sectors, as obtainable in the stocks database presented in Section 3.3.5.

The General Government is divided into two functions: social affairs (GG-SA) and Recovery Plan (GG-RP). This separation allows for a better traceability of the flows and stocks that are related to the Recovery Plan and other affairs that are independent of the plan. Therefore, the institutional sectors that are included are the GG, NPISH, NFC, FC, HH and RoW, as presented in Figure 4.4.

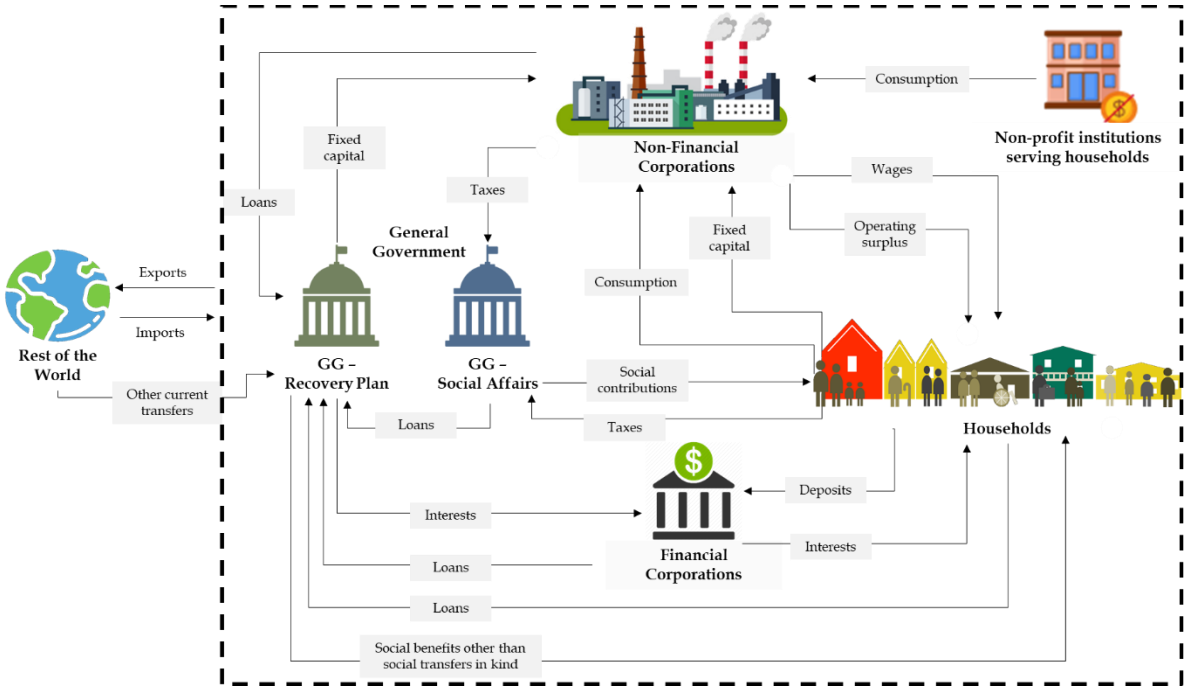


Figure 4.4 | Transactions and institutional sectors included in the case study

Non-financial corporations receive the money from households and the general government (recovery plan) and pay the taxes to the general government (social affairs), wages, and salaries to their employees (households), and transfer one part of the operating surplus to households.

Households pay taxes on income and social contributions to the general government (social affairs), and the remaining money is deposited to financial corporations, which pay interests in the following periods to households. Financial corporations assure the stocks' consistency, providing loans and receiving deposits, and then paying the interests to the concerned institutions.

4.4 Monetary distribution and stock-flow consistency

The monetary distribution of the case study was coded in python, where the equations presented in Section 3.3.4 were applied. Initially, EXIOBASE3 is parsed through *pymrio*.

```
import pymrio
exio3 = pymrio.parse_exiobase3
```

At this point, the perturbation is imported (P), and the Leontief inverse (L) is obtained by using the NumPy library.

```
size = 9800

Matrix_A = exio3.A

L = np.linalg.inv(np.subtract(np.identity(size),Matrix_A))
```

The next step is to calculate the new outputs resulting from the perturbation, which also uses the NumPy library for multiplying two matrixes.

```
X=np.matmul(L,Pert) # new outputs vector X'

X_diag = np.diag(X) # new outputs diagonal matrix
```

The matrix $\tilde{B}$ was calculated in Excel and imported to the Jupyter Notebook because it does not include all elements that are presented in the extension provided by *pymrio*. As explained in Section 3.3.5, three scenarios for operating surplus are proposed, each one implies in a different matrix $\tilde{B}$ and consequently affecting all the following steps.

The matrix G was obtained by multiplying the coefficients matrix $\tilde{B}$ by the new outputs diagonalized matrix $\widehat{X'}$, using the same NumPy function to multiply the matrixes. Concerning imports and exports, the code applied is presented here below.

```
Z_new = np.matmul(Matrix_A,X_diag)

region = "FR"

Z_new.loc[region].to_excel(region + '_outputs.xlsx', sheet_name='outputs', index = True)

num_regions = 49

num_activities = 200

index_region = 10

index_initial = num_activities * index_region

index_final = index_initial + num_activities

Z_new.loc[:,np.arange(index_initial, index_final, 1)].to_excel(region + '_inputs.xlsx',
sheet_name='inputs', index = True)Z_new.loc[:,np.arange(index_initial, index_final,
1)].to_excel(region + '_column.xlsx', sheet_name='columns', index = True)
```

The changes in value-added components are accounted for in the Excel sheet with the TFM registering all the transactions. The equations for obtaining the parameters from Table 3.4 are presented here below. For the operating surplus, NFCs pay for the total amount received by each institutional sector (k), as presented in Equation 4-1.

$$OS^R{}_k = \gamma_k \cdot OS^U{}_{NFC} \qquad \text{Equation 4-1}$$

The parameter "γ" represents the proportions of redistribution of GVA to each institutional sector (k) as presented in Section 3.3.4. Of course, the sum of operating surplus received by each institutional sector equals the amount paid by NFCs, or the sum of γ_k is 1.

The Exiobase value-added components include the wages, salaries and employer's social contributions, which represent the gross expenditures of the employers on labor. These components are normally disaggregated into wages and salaries (represented by the transaction D11 in SNA) and employer's social contributions (represented by the transaction D12 in SNA). In this thesis, the disaggregation was made for distinguishing between the employer's social contribution, which are not a resource for households, but for the government, from the employee's social contributions, which are paid in function of their revenue. For disaggregating the value-added component from Exiobase concerning wages, salaries and employer's social contributions (G_{wse}), the values from the balances for French economy from SNA (Appendix 3) are used.

$$ESC^U{}_{NFC} = \frac{D12}{D11+D12} \cdot G_{wse} \qquad \text{Equation 4-2}$$

$$W^R{}_{HH,i} = \frac{D11}{D11+D12} \cdot G_{wse,i} \text{ (i = low,medium and high-skilled HH)} \qquad \text{Equation 4-3}$$

Households pay taxes on income (TI) and social contributions (SC) to the government, proportionally to their changes in income (θ and ρ) as presented in Equation 4-4 and 4-5.

$$TI^U{}_i = \theta \cdot (W^R{}_i + OS^R{}_i) \qquad \text{Equation 4-4}$$

$$SC^U{}_i = \rho \cdot W^R{}_i \qquad \text{Equation 4-5}$$

Where $\theta = \frac{D5}{D11+B2G}$, and $\rho = \frac{D61-D12}{D11}$.

Both rates (θ and ρ) are obtained from the balances of non-financial transactions for France from SNA (Appendix 3). The rate for the taxes on income (θ) is obtained by dividing the amount of "D5 – current taxes on income and wealth" paid by households by the total income, which is composed of the wages and salaries (D11) and operating surplus (B2G). For social contributions, in SNA, the employer's social contributions (D12) is totally received by households, which are responsible for paying the government through the employee's social contributions (D61). For this reason, the rate for social contributions (ρ) needs to discount the

part of employer's social contribution which was already separated in the method applied here (Equation 4-3).

The values and TFMs are presented in the next sections for both simplified and detailed versions. Table 4.16 presents as a reminder the description of the six scenarios.

Table 4.16: Scenarios description

Total budget (residential and public buildings)	**Only residential** (residential buildings)		**Scenario description**
Simplified	**Detailed**	**Simplified**	
Sc1.a	**Sc2.a**	**Sc3.a**	Operating surplus is paid to each income group following the proportions from compensation of employees
Sc1.b	**Sc2.b**	**Sc3.b**	Total operating surplus is received by high-skilled households
Sc1.c	**Sc2.c**	**Sc3.c**	Total operating surplus is saved by households in its aggregated form

4.4.1 Total budget, simplified version

Scenario Sc1.a

The simplified version of the total budget is analyzed through three scenarios, as presented in Table 4.16. In Sc1.a, the coefficient matrix $\tilde{B}$ presents the operating surplus disaggregated into three income levels. The first step is to obtain the matrix G, also with the operating surplus disaggregated. The values of changes in value-added are accounted for in the TFM, as presented in Table 4.17.

The values highlighted in red represent the perturbation. The GG-RP spends 3.2 billion euros in gross fixed capital formation and 2.0 billion euros in social benefits, such as MPR to HH. This money comes 40% from the European Union, and 60% from loans taken as usual by the Government to finance National policies. The shares of loan issuers are taken from the "Stocks Database", as presented in Section 3.5.

The GG-SA lends 1.0 billion euros to the GG-RP, which can be explained by the different levels of organization (municipal, regional and national) of the Government. The amount of 1.52 billion euros come from the ROW, and the countries that lend money (loan issuers) are taken from the cross-country from-whom-to-whom matrix, also from the "Stocks Database" (See Section 3.5).

NFCs receive, through the construction sector, 5.2 billion euros, which are used to pay the wages and salaries (2.52 billion euros), taxes on products (0.20 billion euros), other taxes on production (0.15 billion euros) and the operating surplus (1.25 billion euros). The change in exports is 0.02 billion euros, while the change in imports is 1.11 billion euros. The

perturbation was applied to the construction work activities, which, according to the EXIOBASE data, imports 13% of its resources.

Table 4.17 | Transaction-flow matrix of first round, first period, Sc1.a

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																	0
Gross capital formation		5.20			3.20				0.47		1.17		0.36				0
Exports of goods and services		0.02													0.02		0
Imports of goods and services	1.11															1.11	0
Operating surplus	1.25	0.71		0.05				0.24		0.01		0.15		0.09	0.44	0.44	0
Wages and salaries	1.89									0.08		1.10		0.71			0
Employer's social contributions	0.63							0.63									0
Taxes on products	0.20							0.20							0.09	0.09	0
Other taxes on production	0.15							0.15							0.03	0.03	0
Interest																	0
Current taxes on income and wealth								0.46	0.02		0.27		0.17				0
Social contributions								0.30	0.01		0.17		0.11				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						2.08									2.08		0
Non-financial net position		0.71		0.05		-3.12		1.98		0.06		0.80		0.51		-1.00	0
Deposits	0.44			0.28			0.99		0.06		0.80		0.51		-2.52		0
Debt	0.27		0.33			3.12	1.00								1.52		0
Financial net position		-0.71		-0.05		3.12		-1.98		-0.06		-0.80		-0.51		1.00	0

Use: uses, Res: resources

The operating surplus is thus distributed to the institutional sectors as explained in Section 3.3.5,p. 81. The shares used in this case followed their contribution to the GVA, as presented in Appendix 3. The shares applied in the case study are shown in Table 4.18.

Table 4.18 | Shares for redistributing the operating surplus

Non Financial Corporations	Financial Corporations	Government	Households and NPISH
56.9%	4.2%	19.2%	19.8%

At the end of the first round of the first period, NFCs are in a net lending position, with 0.71 billion euros that go as a financial asset to the "deposits" account. The money lent to GG-RP (0.3 billion euros) is withdrawn from their "deposits" account resulting in 0.4 billion euros to be deposited to FCs. Therefore, the financial position (B9F) is the sum of both financial assets: 0.4 billion in deposits plus the 0.3 billion euros as loans, matching the non-financial net lending position. FCs intermediate the financial transactions, receiving the total deposits from other institutional sectors and paying the loans to the agents that need to borrow the money.

All three household groups are in a net lending position. Low-skilled HHs had the lowest increase (0.06 billion euros), while medium-skilled HHs had the highest one (0.80 billion euros), followed by the high-skilled HHs (0.51 billion euros). These positive net changes in non-financial transactions result in an increase in financial assets, by means of deposits to

the FCs. However, the observed increase in deposits is only temporary as part of the money received by households is spent in a second round of the same period.

The ROW finances a part of the recovery plan. In the TFM it is possible to see the 2.08 billion euros (40% of total invested money) that are transferred through 'other current transfers', representing the money from the European Union. Besides, the ROW pays for the import transactions and receives the money from exports, as well as all the value-added elements that are generated (paid and received) outside France, that are registered in the TFM for information.

As aforementioned, in addition to the money from European Union, the ROW lends 1.52 billion euros to GG for financing the recovery plan. This money is withdrawn from their financial (current) account through a negative use of the "deposits" account. Therefore, the ROW is in a net borrowing position on the non-financial side and in a net lending position on the financial side of the TFM.

Scenario Sc1.b

The major change between Sc1.b and Sc1.a is the coefficients matrix $\tilde{B}$, which presents the operating surplus aggregated. The first step is to obtain the matrix G, also with operating surplus aggregated. The values of changes in value-added are accounted for in the TFM, as presented in Table 4.19.

Table 4.19 | Transaction-flow matrix of first round, first period, Sc1.b

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																	0
Gross capital formation		5.20			3.20				0.47		1.17		0.36				0
Exports of goods and services		0.02													0.02		0
Imports of goods and services	1.11															1.11	0
Operating surplus	1.25	0.71		0.05				0.24						0.25	0.44	0.44	0
Wages and salaries	1.89									0.08		1.10		0.71			0
Employer's social contributions	0.63							0.63									0
Taxes on products	0.20							0.20							0.09	0.09	0
Other taxes on production	0.15							0.15							0.03	0.03	0
Interest																	0
Current taxes on income and wealth								0.46	0.02		0.24		0.21				0
Social contributions								0.30	0.01		0.17		0.11				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						2.08									2.08		0
Non-financial net position		0.71		0.05		-3.12		1.98		0.05		0.68		0.64		-1.00	0
Deposits	0.44			0.28			0.99		0.05		0.68		0.64		-2.52		0
Debt	0.27		0.33			3.12	1.00								1.52		0
Financial net position		-0.71		-0.05		3.12		-1.98		-0.05		-0.68		-0.64		1.00	0

Use: uses, Res: resources

The main variation in relation to the previous scenario is observed for households. In Sc1.b, high-skilled households present a higher value in lending position, being closer to medium-skilled households. This is expected as high-skilled receive all the money from

operating surplus, which represents around one fourth of total gross revenue of high-skilled in this scenario. The other institutional sectors remain the same as in the previous scenario.

Scenario Sc1.c

In Sc1.c, the entire amount of the operating surplus received by households is saved and does not induce any marginal consumption. For this reason, the financial transactions that occur at the end of the first round should be distinguished between those that will result in consumption (temporarily deposited in household bank accounts) and those that will result in additional income through interest. However, this distinction is only meaningful in the aggregate household form for avoiding the allocation of operating surplus, which is already covered in the Sc1.a. Therefore, the TFM of this scenario, presented in Table 4.20, introduces households aggregated for conducting the balances, however, the wages and salaries are disaggregated into the three income groups for keeping the distinction between their marginal consumption patterns.

Table 4.20 | Transaction-flow matrix of first round, first period, Sc1.c

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH		HH				ROW		Sum
											LS		MS		HS		
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																	0
Gross capital formation		5.20			3.20				2.00		0.47		1.17		0.36		0
Exports of goods and services		0.02														0.02	0
Imports of goods and services	1.11															1.11	0
Operating surplus	1.25	0.71		0.05				0.24		0.25						0.44	0.44	0
Wages and salaries	1.89									1.89		0.08		1.10		0.71		0
Employer's social contributions	0.63							0.63										0
Taxes on products	0.20							0.20								0.09	0.09	0
Other taxes on production	0.15							0.15								0.03	0.03	0
Interest																		0
Current taxes on income and wealth								0.46	0.46		0.02		0.24		0.15			0
Social contributions								0.30	0.30		0.01		0.17		0.11			0
Social benefits other than social transfers in kind					2.00					2.00		0.47		1.17		0.36		0
Other current transfers						2.08										2.08		0
Non-financial net position		0.71		0.05		-3.12		1.98		1.37		0.05		0.68		0.44		-1.00	0
Deposits - temporary				0.81					0.81		0.04		0.47		0.31			0
Deposits - long term	0.44			-0.53			0.99		0.56		0.01		0.22		0.14	-2.52		0
Debt	0.27		0.33			3.12	1.00									1.52		0
Financial net position		-0.71		-0.05		3.12		-1.98		-1.37		-0.05		-0.68		-0.44		1.00	0

Use: uses, Res: resources

The main difference between this scenario and the previous ones lies in the fact of distinguishing the temporary from the long-term deposited money. In Sc1.a and Sc 1.2, all the income received by households is treated as 'temporary' in the financial accounts, since one part of this marginal income is used for consumption in a second round. Here, the distinction is made already in the first round, where €0.78 billion are already saved. An interesting discussion rising from this assumption is what happens with this money, for example, the money saved by households can be invested in corporations and cause a productivity growth. A further discussion on this matter is presented in Chapter 6.

4.4.2 Only residential, detailed version

Scenario Sc2.a

The financial aid coming from the Recovery Plan only cover a part of the money spent in retrofitting works. The detailed version of the economic perturbation allows modeling the money actually spent by households because MENFIS simulates the increase in MPR financial aid providing as an outcome the amount of retrofitting works induced by this increase and the costs for each work. As presented in Section 4.2.2, according to our MENFIS simulations, an increase in €2.00 billion in MPR causes an increase in €6.26 billion of money spent in retrofitting works, i.e., approximately two-thirds of the money spent in retrofitting is financed by other aids or come from the saved money of households.

The source of money to pay for the thermal retrofitting works (accounted as total gross fixed capital formation) is an important element for building a TFM. Here, the assumption is that households take out zero-interest loans to finance the remaining part of their retrofitting work, which is the financial aid most often adopted when combined with MPR for the simplicity of joining them in the bank procedures (Effy, 2022). Table 4.21 presents the TFM for the first round of the first period, for the scenario Sc2.a.

Table 4.21 | Transaction-flow matrix of first round, first period, Sc2.a

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																	0
Gross capital formation		5.80							0.71		3.40		1.68				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.32															1.32	0
Operating surplus	1.26	0.72		0.05				0.24		0.01		0.11		0.12	0.53	0.53	0
Wages and salaries	2.10									0.08		0.96		1.06			0
Employer's social contributions	0.71							0.71									0
Taxes on products	0.24							0.24							0.10	0.10	0
Other taxes on production	0.20							0.20							0.03	0.03	0
Interest																	0
Current taxes on income and wealth								0.51	0.02		0.23		0.26				0
Social contributions								0.33	0.01		0.15		0.17				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						0.80									0.80		0
Non-financial net position		0.72		0.05		-1.20		2.23		-0.18		-1.54		-0.57		0.50	0
Deposits	0.61			3.88			1.85		0.06		0.69		0.76		-0.09		0
Debt	0.10		3.93			1.20	0.38			0.24		2.24		1.33	0.58		0
Financial net position		-0.72		-0.05		1.20		-2.23		0.18		1.54		0.57		-0.50	0

Use: uses, Res: resources

Low-skilled HH spend €0.71 billion in retrofitting works, €0.47 billion come from MPR primes and €0.24 billion come from free-interest loans. In the monetary distribution process, €0.08 billion return to low-skilled HHs, of which they spend €0.03 billion in taxes and social contributions. Therefore, at the end of this first round, they are in a net borrowing position, as

expected, since they took on loans (free-interest loans) to finance their retrofitting works. Even though, they transfer €0.06 billion as temporary deposits to FCs, which induces consumption in the second round. This also happens for the other two income groups: medium-skilled HHs transfer €0.69 billion as temporary deposits to FCs and high-skilled HHs transfer €0.76 billion to FCs. The total money that triggers the induced consumption is €1.51 billion, which will be partly saved and partly spent on consumption goods and services.

The NFCs receive €5.80 billion and redistribute the greatest part of the received money to FCs as operating surplus, HHs as wages and salaries, GG-SA as social contributions and operating surplus and ROW by importing goods and services. As in previous scenarios, their net lending position corresponds to the surplus that they receive, which is €0.72 billion here.

The GG-RP is the other institutional sector in a net borrowing position as they take on loans of €1.2 billion to finance the Recovery Plan.

Scenario Sc2.b

In the detailed version, the major changes in relation to the previous scenario concern the change in net wealth of each income group of households and also the temporary transfers as deposits to FCs, as presented in Table 4.22. Even if the total money transferred from the three income groups to FCs (€1.51 billion) is the same as in scenario Sc2.a, the change in the proportions of the three income groups will affect the second round. This is because each income group saves money at different rates and presents its own consumption pattern. The other institutional sectors do not present any change in relation to the previous scenario.

Table 4.22 | Transaction-flow matrix of first round, first period, Sc2.b

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																	0
Gross capital formation		5.80							0.71		3.40		1.68				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.32															1.32	0
Operating surplus	1.26	0.72		0.05				0.24						0.25	0.53	0.53	0
Wages and salaries	2.10									0.08		0.96		1.06			0
Employer's social contributions	0.71							0.71									0
Taxes on products	0.24							0.24							0.10	0.10	0
Other taxes on production	0.20							0.20							0.03	0.03	0
Interest																	0
Current taxes on income and wealth								0.51	0.02		0.21		0.28				0
Social contributions								0.33	0.01		0.15		0.17				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						0.80									0.80		0
Non-financial net position		0.72		0.05		-1.20		2.23		-0.19		-1.63		-0.47		0.50	0
Deposits	0.61			3.88			1.85		0.05		0.60		0.86		-0.09		0
Debt	0.10		3.93			1.20	0.38			0.24		2.24		1.33	0.58		0
Financial net position		-0.72		-0.05		1.20		-2.23		0.19		1.63		0.47		-0.50	0

Use: uses, Res: resources

Scenario Sc2.c

In the detailed version, as well as in the simplified version, the third scenario presents the results of households in the aggregated form and the deposits divided into temporary and long-term for distinguishing between the money that induces consumption in a second period and the money that is stocked and saved. Table 4.23 shows the results of the TFM at the end of the first round of the first period.

Table 4.23 | Transaction-flow matrix of first round, first period, Sc2.c

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH		HH						ROW		Sum
											LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																			0
Gross capital formation		5.80							5.80										0
Exports of goods and services		0.03															0.03		0
Imports of goods and services	1.32																	1.32	0
Operating surplus	1.26	0.72		0.05				0.24		0.25							0.53	0.53	0
Wages and salaries	2.10									2.10		0.08		0.96		1.06			0
Employer's social contributions	0.71							0.71											0
Taxes on products	0.24							0.24									0.10	0.10	0
Other taxes on production	0.20							0.20									0.03	0.03	0
Interest																			0
Current taxes on income and wealth								0.51	0.51		0.02		0.21		0.23				0
Social contributions								0.3	0.33		0.01		0.15		0.17				0
Social benefits other than social transfers in kind					2.0					2.00									0
Other current transfers						0.8											0.80		0
Non-financial net position		0.72		0.05		-1.20		2.23		-2.29		0.05		0.60		0.66		0.50	0
Deposits - temporary				0.91					0.91		0.04		0.41		0.46				0
Deposits - long term	0.6			2.97			1.85		0.60		0.01		0.19		0.20		-0.09		0
Debt	0.1		3.93			1.20	0.38			3.80							0.58		0
Financial net position		-0.72		-0.05		1.20		-2.23		2.29		-0.05		-0.60		-0.66		-0.50	0

Use: uses, Res: resources

The amount of €0.91 billion transferred from HHs to FCs corresponds to the money to be spent in a second round of (re)distribution. This value is lower than the total deposited money of households from previous periods (€1.51 billion). This is because, in the previous scenarios, the 'deposits' are not disaggregated into temporary and long-term deposits. Therefore, the total deposits of the three income groups in scenarios Sc2.a and Sc2.b is comparable to the sum of temporary and long-term deposits of aggregated HHs in scenario Sc2.c.

As well as in the previous scenario, the other institutional sectors do not change in relation to the initial scenario Sc2.a.

4.4.3 Only residential, simplified version

Scenario Sc3.a

The simplified version of the perturbation considering only residential building consists of 5.80 billion of expenditures, coming from households to non-financial corporations, where the only product affected in the foreground is the "construction works". The TFM for scenario Sc3.a, where the operating surplus is distributed to each income group following the same proportions as the wages and salaries, is presented in Table 4.24.

Table 4.24 | Transaction-flow matrix of first round, first period, Sc3.a

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																	0
Gross capital formation		5.80							1.38		3.39		1.04				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.23															1.23	0
Operating surplus	1.39	0.79		0.06				0.27		0.01		0.17		0.10	0.49	0.49	0
Wages and salaries	2.10									0.09		1.22		0.79			0
Employer's social contributions	0.71							0.71									0
Taxes on products	0.23							0.23							0.10	0.10	0
Other taxes on production	0.16							0.16							0.03	0.03	0
Interest																	0
Current taxes on income and wealth								0.52	0.02		0.30		0.19				0
Social contributions								0.33	0.01		0.19		0.13				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						0.80									0.80		0
Non-financial net position		0.79		0.06		-1.20		2.21		-0.84		-1.33		-0.11		0.41	0
Deposits	0.69			3.87			1.83		0.06		0.89		0.57		-0.18		0
Debt	0.10		3.93			1.20	0.38			0.90		2.22		0.68	0.58		0
Financial net position		-0.79		-0.06		1.20		-2.21		0.84		1.33		0.11		-0.41	0

Use: uses, Res: resources

There are two main differences when compared with the detailed version. The first one concerns how much each income group spend on thermal retrofitting services. In this version, low-skilled HHs double their expenditure in relation to the detailed version, while high-skilled

households reduce by 40% the money spent on capital formation. Medium-skilled HHs do not change their expenditure. The second difference lies in the proportions of the value-added components. In this version, the operating surplus is higher than detailed version, while taxes are lower. Therefore, the resources of the general government are lower than in the previous version, while households have a higher income in this version. These differences are also true for scenarios Sc3.b and Sc3.c.

Scenario Sc3.b

In this scenario, as well as for versions of total budget and detailed residential buildings, the main difference concerns the medium-skilled and high-skilled HHs. Medium-skilled HHs have a drop in their income because they do not receive operating surplus while high-skilled HHs increase considerably their income. These changes have an effect in the following rounds of distribution as they save at different rates and do not have the same consumption patterns. Low-skilled HHs are also affected, however, in a lower proportion as the other two income groups. Table 4.25 presents the TFM for the first round of the first period for scenario Sc3.b.

Table 4.25 | Transaction-flow matrix of first round, first period, Sc3.b

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																	0
Gross capital formation		5.80							1.38		3.39		1.04				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.23															1.23	0
Operating surplus	1.39	0.79		0.06				0.27						0.28	0.49	0.49	0
Wages and salaries	2.10									0.09		1.22		0.79			0
Employer's social contributions	0.71							0.71									0
Taxes on products	0.23							0.23							0.10	0.10	0
Other taxes on production	0.16							0.16							0.03	0.03	0
Interest																	0
Current taxes on income and wealth								0.52	0.02		0.27		0.23				0
Social contributions								0.33	0.01		0.19		0.13				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						0.80									0.80		0
Non-financial net position		0.79		0.06		-1.20		2.21		-0.85		-1.46		0.03		0.41	0
Deposits	0.69			3.87			1.83		0.06		0.76		0.71		-0.18		0
Debt	0.10		3.93			1.20	0.38			0.90		2.22		0.68	0.58		0
Financial net position		-0.79		-0.06		1.20		-2.21		0.85		1.46		-0.03		-0.41	0

Use: uses, Res: resources

Scenario Sc3.c

Table 4.26 presents the TFM for scenario Sc3.c, where all the operating surplus is saved by HHs, in its aggregated form. In the end of the first round, HHs have €0.91 billion in temporary deposits to spend in a second round of distribution, while 0.62 billion is saved. The other institutional sectors do not have any particular alteration from what was previously discussed.

Table 4.26 | Transaction-flow matrix of first round, first period, Sc3.c

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH		HH						ROW		Sum
											LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure																			0
Gross capital formation		5,80								5,80	1,38		3,39		1,04				0
Exports of goods and services		0,03															0,03		0
Imports of goods and services	1,23																	1,23	0
Operating surplus	1,39	0,79		0,06				0,27		0,28							0,49	0,49	0
Wages and salaries	2,10									2,10		0,09		1,22		0,79			0
Employer's social contributions	0,71							0,71											0
Taxes on products	0,23							0,23									0,10	0,10	0
Other taxes on production	0,16							0,16									0,03	0,03	0
Interest																			0
Current taxes on income and wealth								0,52	0,52		0,02		0,27		0,17				0
Social contributions								0,33	0,33		0,01		0,19		0,13				0
Social benefits other than social transfers in kind					2,00					2,00		0,47		1,17		0,36			0
Other current transfers						0,80											0,80		0
Non-financial net position		0,79		0,06		-1,20		2,21		-2,27		-0,85		-1,46		-0,18		0,41	0
Deposits - temporary				0,91					0,91		0,04		0,52		0,34				0
Deposits - long term	0,69			2,97			1,83		0,62		0,01		0,24		0,15		-0,18		0
Debt	0,10		3,93			1,20	0,38			3,80		0,90		2,22		0,68	0,58		0
Financial net position		-0,79		-0,06		1,20		-2,21		2,27		0,85		1,46		0,18		-0,41	0

Use: uses, Res: resources

4.5 Monetary redistribution and stock-flow consistency

The second round of monetary (re)distribution occurs when the money instantaneously cumulated in the first round is spent in consumption goods and services. Two major challenges take place when linking the two first rounds: to identify how much money cumulated in the first round is spent in the second round (α factor for each income group) and to identify how the money is spent ($\tilde{C}$, marginal consumption patterns matrix), as described in Section 3.3.6.

Considering that the EXIOBASE3 datasets provide the consumption of households aggregated as an institutional sector, disaggregation is needed in terms of the three income groups. In the case study, the assumptions are the same for both approaches (simplified and detailed). In 2018 the INSEE asked to the French households the question "If your income increased, how would you spend the extra money?" (Lelièvre and Remila, 2018a). Their results are presented per household income group, divided into four categories: **low income**, **lower income**, **middle class** and **wealthy**. Their classification is based on the level of poverty defined by the French Department of Research, Studies, Evaluation and Statistics (DREES, for French *Direction de la Recherche, des études, de l'évaluation et des statistiques* (DREES)). **Low income** classification concerns the households having an income lower than the poverty threshold, **lower income** corresponds to the households that receive more than the poverty threshold and less than the fourth decile threshold. **Middle class** households have an income of more than the fourth decile threshold and less than the third quartile, and **wealthy** households correspond to the group having an income of more than the third quartile threshold (Lelièvre & Remila, 2018b, box 1).

Figure 4.5 presents the correspondence of this classification with that of the ILO. Since no disaggregated data is provided, the simplest approach was applied in this case study: low income corresponds to low-skilled, lower-income and middle class correspond to the medium-skilled households and wealthy corresponds to high-skilled households.

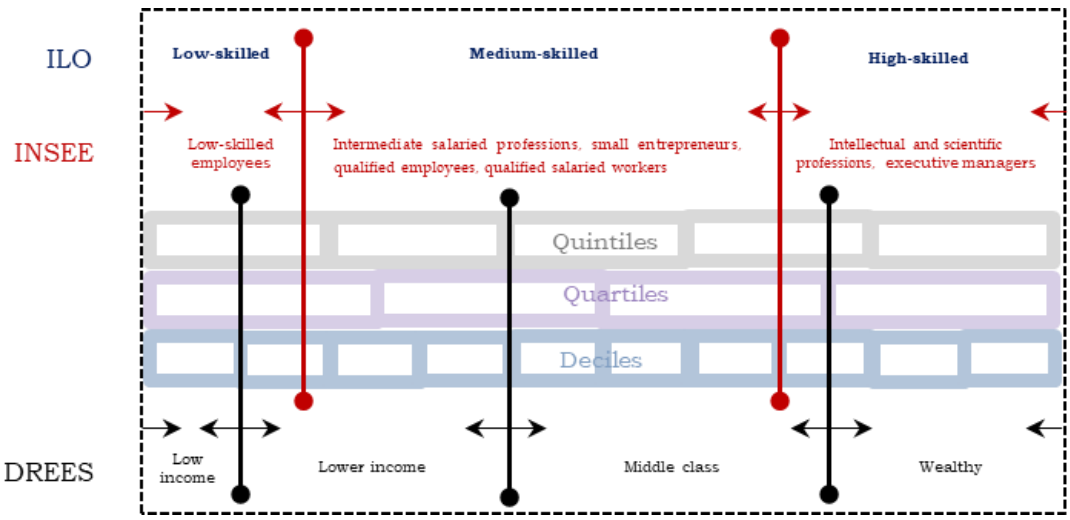


Figure 4.5 | Correspondence between the ILO and DREES socio-economic classifications

Considering that no disaggregated data is publicly available, the simplest approach is applied in this case study: low income corresponds to low-skilled, lower-income and middle class correspond to the medium-skilled households and wealthy corresponds to high-skilled households. These linkages are conducted for the purpose of identifying what each income group does with the extra money received, or, marginal consumption patterns. Table 4.27 presents the results by category of consumption goods and services, which must be associated with the EXIOBASE activities.

Table 4.27 | Distribution of expenditures of hypothetical increase in income, per income group

Category of consumed goods and services	Low-skilled	Medium-Skilled	High-skilled
Food	27%	14%	4%
Clothing	6%	7%	2%
Housing	11%	14%	20%
Home furnishings	12%	16%	18%
Healthcare	9%	7%	4%
Transport (including buying new vehicles)	5%	5%	4%
Leisure activities	24%	34%	46%
Culture and education	6%	3%	4%

Food industry is disaggregated into twenty-seven main products, as listed below:

- Meat products n.e.c.
- Vegetables, fruit, nuts
- Products of meat poultry
- Products of meat cattle
- Poultry
- Products of meat pigs
- Meat animals n.e.c.
- Wheat
- Fish and other fishing products; services incidental of fishing
- Oil seeds
- Plant-based fibers
- Cereal grains n.e.c.
- products of Vegetable oils and fats
- Processed rice
- Paddy rice
- Sugar cane, sugar beet
- Crops ne.c.
- Cattle
- Pigs
- Animal products n.e.c.
- Raw milk
- Wool, silk-worm cocoons
- Dairy products
- Sugar
- Food products n.e.c.
- Beverages
- Fish products

The proportions of the final consumption of French households of the EXIOBASE food products that represent more than 1% of the total are presented in

Table 4.28. Around 60% of the households final consumption of food products consists of French products. The remaining 40% of the consumed food products come from other countries, for example, vegetables, fruit and nuts from Africa (WF) and Spain (ES), food products from Germany (DE), Spain (ES), Italy (IT) and the Netherlands (NL).

Table 4.28 | Final consumption of French food products, total households

Region	EXIOBASE product	Percentage of HH final consumption
FR	Meat products n.e.c.	19%
FR	Vegetables, fruit, nuts	11%
FR	Products of meat poultry	10%
FR	Products of meat cattle	6%
FR	Poultry	4%
WF	Vegetables, fruit, nuts	3%
FR	Products of meat pigs	3%
DE	Food products n.e.c.	3%
FR	Meat animals n.e.c.	3%
BE	Food products n.e.c.	2%
ES	Vegetables, fruit, nuts	2%
NL	Food products n.e.c.	2%
FR	Wheat	2%
FR	Fish and other fishing products; services incidental of fishing	2%
ES	Food products n.e.c.	1,6%
IT	Food products n.e.c.	1,4%

FR: France, IT: Italy, ES: Spain, BE: Belgium, WF: RoW Africa, DE: Germany, NL: Netherlands

No information on the preferences of each income group for food products was available, therefore, the averages were taken into account for the purpose of the thesis.

For 'Clothing', the activities "Textiles" and "Leather and leather products" were considered as the products purchased by households when they have some extra income and decide to buy clothes. EXIOBASE's total expenditure of households in these two activities is 15 billion euros, however, only 1% in France according to the data for 2020 (0 MEUR for textiles and 157 MEUR for leather products). The original data from EXIOBASE3 monetary IOT from 2011 presented a final consumption of 12 billion of textiles and leather, being 20% produced in France. Therefore, the zero value for the production of textiles in France can be considered as lacking data in this dataset. For this reason, the increase in demand observed for leather products from 2011 to 2020 was applied to the textiles.

The resulting table of the proportions of each activity (textiles and leather products) for all countries that represent more than 2% of the consumed clothing products by French households are presented in Table 4.29.

Table 4.29 | Clothing activities consumed by French households

Region	Activity	Final consumption expenditure by French households
FR	Textiles	21%
IT	Leather and leather products	12%
CN	Leather and leather products	8%
CN	Textiles	5%
ES	Leather and leather products	5%
BE	Textiles	4%
IT	Textiles	4%
WA	Textiles	3%
DE	Textiles	3%
WF	Textiles	3%
WF	Leather and leather products	3%
PT	Leather and leather products	3%
DE	Leather and leather products	3%
ES	Textiles	2%
TR	Textiles	2%
IN	Leather and leather products	2%

FR: France, IT: Italy, CN: China, ES: Spain, BE: Belgium, WA: RoW Asia and Pacific WF: RoW Africa, DE: Germany, PT: Portugal, TR: Turkey, IN: India

Marginal expenditures in 'Housing' means that households would buy, build or rent a new house (or, yet, a second house). Therefore, the two activities that are associated with it are construction works and real estate services. The latter dominates the average expenditures of households with concern to housing, representing 95%, while the construction works represent the remaining 5%, all production occurring in France. This involves an important limitation concerning the available data since average expenditures in housing are applied rather than the marginal data.

'Home furnishing' is a wide category and can be associated with multiple activities. For the purpose of the thesis, the four products considered were as follows: machinery and equipment n.e.c., wholesale trade and commission trade services, except for motor vehicles and motorcycles, retail trade services, except for motor vehicles and motorcycles; repair services of personal and household goods, and computer and related services. The great majority of the consumed products are produced in France, as presented in Table 4.30.

Table 4.30 | Home-furnishing products consumed by French households

Region	EXIOBASE activity	Percentage of total home furnishing consumption
FR	Wholesale trade and commission trade services, except of motor vehicles and motorcycles	53.7%
FR	Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods	37.1%
FR	Machinery and equipment n.e.c.	3.3%
DE	Machinery and equipment n.e.c	1.1%
IT	Machinery and equipment n.e.c.	0.5%
FR	Computer and related services	0.5%
CN	Machinery and equipment n.e.c.	0.4%

FR: France, IT: Italy, DE: Germany, CN: China

The expenditures in 'Healthcare' are attributed to the activity "Health and social work services", which is consumed 99% in France, as expected. Table 4.31 presents the services that represent more than 0.1% of total Healthcare services consumed by French households.

Table 4.31 | Transport products consumed by French households

Region	Sector	Percentage of total Healthcare services consumption
FR	Health and social work services	98,9%
WF	Health and social work services	0,3%
WA	Health and social work services	0,2%
WM	Health and social work services	0,2%
GB	Health and social work services	0,13%

FR: France, WA: ROW Asia and Pacific WF: RoW Africa, WM: Middle East, GB: Great Britain

The money spent on 'Transport' includes buying new cars, repairing current in-use cars and other activities. The selected EXIOBASE to represent this consumption are motor vehicles, trailers and semi-trailers, and sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motorcycles parts and accessories. The part of the production that occurs in France represents 61%, as presented in Table 4.32.

Table 4.32 | Transport products consumed by French households

Region	EXIOBASE activity	Percentage of total transport consumption
FR	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	35%
FR	Motor vehicles, trailers and semi-trailers	26%
DE	Motor vehicles, trailers and semi-trailers	10%
ES	Motor vehicles, trailers and semi-trailers	7%
WF	Motor vehicles, trailers and semi-trailers	4%
IT	Motor vehicles, trailers and semi-trailers	3%
BE	Motor vehicles, trailers and semi-trailers	2%
GB	Motor vehicles, trailers and semi-trailers	1%
PL	Motor vehicles, trailers and semi-trailers	1%
SK	Motor vehicles, trailers and semi-trailers	1%
CZ	Motor vehicles, trailers and semi-trailers	1%
SE	Motor vehicles, trailers and semi-trailers	1%
NL	Motor vehicles, trailers and semi-trailers	1%
TR	Motor vehicles, trailers and semi-trailers	1%
PT	Motor vehicles, trailers and semi-trailers	1%
JP	Motor vehicles, trailers and semi-trailers	1%
RO	Motor vehicles, trailers and semi-trailers	1%

FR: France, IT: Italy, DE: Germany, ES: Spain, WF: ROW of Africa, BE: Belgium, GB: Great Britain, PL: Poland, SK: Slovakia, CZ: Czech Republic, SE: Sweden, NL: Netherlands, TR: Turkey, PT: Portugal, JP: Japan, RO: Romania

'Leisure activities' are described in the survey report as leisure activities including vacations, hotels and restaurants. Therefore, the selected EXIOBASE activities to represent this consumption are the following: hotel and restaurant services, railway transportation services,

other land transportation services, air transport services, and supporting and auxiliary transport services; travel agency services. The proportions of each activity that represent more than 1% of total expenditure on leisure activities are presented in Table 4.33.

Table 4.33 | Leisure service consumed by French households

Region	EXIOBASE activity	Percentage of total leisure consumption
FR	Hotel and restaurant services	49%
FR	Other land transportation services	14%
FR	Supporting and auxiliary transport services; travel agency services	12%
FR	Railway transportation services	10%
FR	Air transport services	8%
US	Air transport services	1%
WA	Air transport services	1%

FR: France, US: United States, WA: ROW Asia and Pacific

The 'Culture and Education' category in the survey corresponds to expenditures in the cultural activities, such as theater, movies, sport events, music concerts, and also the money spent in education in general, as in schools or increasing the number of extra-curricular activities. The two selected EXIOBASE activities to represent this expenditure are recreational, cultural and sporting services, and education services. The percentages of the activities that represent more than 0.2% of total French households consumption with regard to culture and education are presented in Table 4.34.

Table 4.34 | Culture and education services consumed by French households

Region	EXIOBASE activity	Percentage of total education and culture consumption
FR	Recreational, cultural and sporting services	60%
FR	Education services	36%
CH	Recreational, cultural and sporting services	0.4%
IE	Recreational, cultural and sporting services	0.3%
LU	Recreational, cultural and sporting services	0.3%
CA	Recreational, cultural and sporting services	0.3%
GB	Recreational, cultural and sporting services	0.3%
BE	Recreational, cultural and sporting services	0.3%

FR: France, CH: Switzerland, IE: Ireland, LU: Luxembourg, CA: Canada, GB: United Kingdom, BE: Belgium

From

Table 4.28 to Table 4.34, the main products and services consumed by French households that are affected by the marginal expenditure created in the second distribution round are shown. These proportions follow the consumption patterns of households in aggregated form; however, the amounts of each category of goods and services vary among the three income groups as presented in Table 4.27.

The new perturbation for the second round is thus the sum of the induced consumption from the three income groups, as previously detailed, with products and services coming from the domestic market and also imported from other countries and regions.

4.5.1 Total budget, simplified version

Scenario Sc1.a

Table 4.35 presents the TFM for the second round of the first period, i.e., the induced consumption, which is highlighted in red in the table. Part of the money goes to the ROW as households import products for their final consumption.

Table 4.35 | Transaction-flow matrix of second round, first period, Sc1.a

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.81							0.04		0.55		0.35			0.13	0
Gross capital formation																	0
Exports of goods and services		0.00													0.00		0
Imports of goods and services	0.08															0.08	0
Operating surplus	0.27	0.15		0.01				0.05		0.00		0.03		0.02	0.08	0.08	0
Wages and salaries	0.30									0.02		0.14		0.14			0
Employer's social contributions	0.10							0.10									0
Taxes on products	0.02							0.02							0.02	0.02	0
Other taxes on production	0.04							0.04							0.00	0.00	0
Interest																	0
Current taxes on income and wealth								0.08	0.00		0.04		0.04				0
Social contributions								0.05	0.00		0.02		0.02				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		0.15		0.01		0.00		0.34		-0.03		-0.44		-0.25		0.20	0
Deposits	0.15		0.00	-0.01			0.34		-0.03		-0.44		-0.25		0.20		0
Debt																	0
Financial net position		-0.15		-0.01		0.00		-0.34		0.03		0.44		0.25		-0.20	0

Use: uses, Res: resources

In this second round, households consume a total of €0.95 billion , €0.81 billion in French products and services and €0.13 billion in imported goods and services. In the French economy, this extra consumption causes an increase of €0.004 billion in exports, €0.08 billion in imports, €0.27 billion in operating surplus, €0.30 billion in wages and salaries, €0.10 billion in employer's social contributions, 0.06 billion euros in overall domestic taxes. Therefore, from the €1.37 billion that were temporarily transferred to household financial accounts at the end

of the first round, €0.82 billion are redistributed to the French institutional sectors in the second round.

The NFCs and FCs are in a net lending position since they receive a part of the operating surplus, as well as the GG-SA, which besides the operating surplus, also receives the taxes. All three HH groups are in a net borrowing position, which is expected since they need the money from the previous round to finance their consumption. The global balance for the first period, which sums the first and second distribution rounds, is thus presented in Table 4.36.

Table 4.36 | Transaction-flow matrix at the end of first period, Sc1.a

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.81							0.04		0.55		0.35			0.13	0
Gross capital formation		5.20			3.20				0.47		1.17		0.36				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.18															1.18	0
Operating surplus	1.52	0.87		0.06				0.29		0.01		0.18		0.11	0.52	0.52	0
Wages and salaries	2.19									0.10		1.23		0.85			0
Employer's social contributions	0.74							0.74									0
Taxes on products	0.23							0.23							0.10	0.10	0
Other taxes on production	0.19							0.19							0.03	0.03	0
Interest																	0
Current taxes on income and wealth								0.54	0.02		0.31		0.21				0
Social contributions								0.35	0.02		0.20		0.13				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						2.08									2.08		0
Non-financial net position		0.87		0.06		-3.12		2.33		0.03		0.36		0.26		-0.79	0
Deposits	0.59		0.00	0.27			1.33		0.03		0.36		0.26		-2.31		0
Debt	0.27		0.33			3.12	1.00								1.52		0
Financial net position		-0.87		-0.06		3.12		-2.33		-0.03		-0.36		-0.26		0.79	0

Use: uses, Res: resources

At the end of the first round, the NFCs and FCs are in a net lending position resulting from the two distribution rounds, mainly due to the operating surplus received in each round.

The GG is in a net borrowing position when summing both functions. The GG-RP is naturally in a net borrowing position because of the money needed for investing in the recovery plan, which is partially recovered by the monetary (re)distribution (nearly 75% of the borrowed money is recovered by the GG-SA).

The other institutional sector that is in a net borrowing position is the ROW, because of the money lent to finance the recovery plan. As well as the government, they recover a part of the lent money due to the increase in imports from French industries and also from goods and services consumed by French households.

Finally, the three income groups of households are in a net lending position mainly because all their initial expenditures were government financed.

Scenario Sc1.b

Table 4.37 presents the TFM of the second round of distribution. In this scenario, the total final consumption of households has no relevant change in relation to the previous scenario, however, the consumption of imported products and services decreased by 2.5%, meaning that the high-skilled households import less products and services than the other income groups. Because of this particularity, the net wealth of all French institutional sectors is higher than in the previous scenario.

Table 4.37 | Transaction-flow matrix of second round, first period, Sc1.b

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.82							0.04		0.47		0.44			0.13	0
Gross capital formation																	0
Exports of goods and services		0.00													0.00		0
Imports of goods and services	0.07															0.07	0
Operating surplus	0.28	0.16		0.01				0.05						0.05	0.08	0.08	0
Wages and salaries	0.31									0.02		0.14		0.15			0
Employer's social contributions	0.10							0.10									0
Taxes on products	0.02							0.02							0.02	0.02	0
Other taxes on production	0.04							0.04							0.00	0.00	0
Interest																	0
Current taxes on income and wealth								0.08	0.00		0.03		0.04				0
Social contributions								0.05	0.00		0.02		0.02				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		0.16		0.01		0.00		0.35		-0.02		-0.38		-0.31		0.20	0
Deposits	0.16		-0.01	-0.01			0.35		-0.02		-0.38		-0.31		0.20		0
Debt																	0
Financial net position		-0.16		0.00		0.00		-0.35		0.02		0.38		0.31		-0.20	0

Use: uses, Res: resources

As well as for the previous scenario, the results at the end of the first period are presented for Scenario Sc1.b (Table 4.38). At the end of the first period, the global results are similar to the ones presented in Table 4.36, with the exception of the households net position, for the same reasons as for the previous version.

Table 4.38 | Transaction-flow matrix at the end of first period, Sc1.b

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure	0.82								0.04		0.47		0.44			0.13	0
Gross capital formation	5.20				3.20				0.47		1.17		0.36				0
Exports of goods and services	0.03														0.03		0
Imports of goods and services	1.18															1.18	0
Operating surplus	1.53	0.87		0.06				0.29						0.30	0.51	0.51	0
Wages and salaries	2.19									0.10		1.24		0.85			0
Employer's social contributions	0.74							0.74									0
Taxes on products	0.23							0.23							0.10	0.10	0
Other taxes on production	0.19							0.19							0.03	0.03	0
Interest																	0
Current taxes on income and wealth								0.54	0.02		0.27		0.25				0
Social contributions								0.35	0.02		0.20		0.14				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						2.08									2.08		0
Non-financial net position		0.87		0.06		-3.12		2.33		0.03		0.30		0.33		-0.80	0
Deposits	0.60		-0.01	0.27			1.33		0.03		0.30		0.33		-2.32		0
Debt	0.27		0.33			3.12	1.00								1.52		0
Financial net position		-0.87		-0.05		3.12		-2.33		-0.03		-0.30		-0.33		0.80	0

Use: uses, Res: resources

Scenario Sc1.c

Scenario Sc1.c disaggregates the households into the three income groups only for accounting for the wages and salaries payment since this is the source of induced consumption in the second round of distribution. However, the overall analysis is more meaningful in the aggregated form.

As more money is saved, the total final consumption is 14% lower than the previous scenario. This decrease in money circulating in the economy affects the net wealth of all French institutional sectors as well as the ROW, as presented in Table 4.39.

Table 4.39 | Transaction-flow matrix of second round, first period, Sc1.c

(Billion euros)	NFC		FC		GG-RP	GG-SA		HH		HH						ROW		Sum
										LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res		
Final consumption expenditure		0.70						0.81		0.04		0.47		0.31			0.11	0
Gross capital formation																		0
Exports of goods and services		0.00														0.00		0
Imports of goods and services	0.06																0.06	0
Operating surplus	0.23	0.13		0.01			0.04		0.05							0.30	0.30	0
Wages and salaries	0.26								0.3		0.0		0.1		0.1			0
Employer's social contributions	0.09						0.09											0
Taxes on products	0.02						0.02									0.02	0.02	0
Other taxes on production	0.03						0.03									0.00	0.00	0
Interest																		0
Current taxes on income and wealth							0.07	0.07		0.00		0.03		0.03				0
Social contributions							0.04	0.04		0.00		0.02		0.02				0
Social benefits other than social transfers in kind																		0
Other current transfers																		0
Non-financial net position		0.13		0.01	0.00		0.29		-0.61		-0.03		-0.39		-0.23		0.18	0
Deposits - temporary			0.81						0.81		0.04		0.47		0.31			0
Deposits - long term	0.13			0.93		0.29		0.20		0.01		0.07		0.08		0.30		0
Loans																		0
Equities and insurances																		0
Financial net position		-0.13		0.12	0.00		-0.29		0.61		0.03		0.39		0.23		-0.30	0

Use: uses, Res: resources

As well as for the previous scenarios, the analysis of at the end of the period is more appropriate for understanding the combined mechanisms. Table 4.40 presents the balances at the end of the first period for Scenario Sc1.c.and the results of them.

The money deposited in the temporary deposits account is entirely used at the end of the first period. The most significant difference between the results of scenario Sc1.c and the previous ones concerns the wealth of households. In this scenario, they are 15% richer than in the previous scenarios because the money received from the operating surplus is 100% saved.

On the other hand, NFCs and FCs decrease their wealth by 3% as less money circulates in the economy. In addition, the ROW is more indebted in this scenario (decrease of 3% in the net wealth) because the expenses to finance the Recovery Plan are the same as in previous scenarios; however, they receive less money from the products imported by French households and from French industries.

Table 4.40 | Transaction-flow matrix at end of first period, Sc1.c

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH		HH						ROW		Sum
											LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.70							0.81		0.04		0.47		0.31			0.11	0
Gross capital formation		5.20			3.20				2.00		0.47		1.17		0.36				0
Exports of goods and services		0.03															0.03		0
Imports of goods and services	1.17																	1.17	0
Operating surplus	1.48	0.84		0.06				0.28		0.29							0.74	0.74	0
Wages and salaries	2.15									2.15		0.10		1.22		0.83			0
Employer's social contributions	0.72							0.72											0
Taxes on products	0.22							0.22									0.10	0.10	0
Other taxes on production	0.18							0.18									0.03	0.03	0
Interest																			0
Current taxes on income and wealth								0.53	0.53		0.02		0.26		0.18				0
Social contributions								0.34	0.34		0.02		0.19		0.13				0
Social benefits other than social transfers in kind					2.00					2.00		0.47		1.17		0.36			0
Other current transfers						2.08											2.08		0
Non-financial net position		0.84		0.06		-3.12		2.28		0.76		0.02		0.29		0.22		-0.82	0
Deposits - temporary			0.81	0.81					0.81	0.81	0.04	0.04	0.47	0.47	0.31	0.31			0
Deposits - long-term	0.57			0.40			1.28		0.76		0.02		0.29		0.22		-2.21		0
Loans	0.27		0.33			3.12	1.00										1.52		0
Financial net position		-0.84		0.07		3.12		-2.28		-0.76		-0.02		-0.29		-0.22		0.70	0

Use: uses, Res: resources

4.5.2 Only residential, detailed version

Scenario Sc2.a

The initial perturbation for the detailed version is an increase in gross fixed capital formation of €5.80 billion, as presented in Section 4.4.2**Erreur ! Source du renvoi introuvable.**. At the end of the first round, this perturbation resulted in increases of €0.06 billion in low-skilled HH temporary net wealth, €0.69 billion of medium-skilled HHs temporary wealth, and €0.76 billion of high-skilled HHs. These increases caused a total induced consumption of €1.04 billion in the second round. Table 4.41 shows the final balance at the end of the first period, consolidating the transactions occurring in the first and second rounds.

Table 4.41 | Transaction-flow matrix at the end of first period, Sc2.a

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.90							0.04		0.47		0.52			0.14	0
Gross capital formation		5.80							0.71		3.40		1.68				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.40															1.40	0
Operating surplus	1.56	0.89		0.07				0.30		0.01		0.14		0.15	0.62	0.62	0
Wages and salaries	2.44									0.10		1.12		1.22			0
Employer's social contributions	0.82							0.82									0
Taxes on products	0.27							0.27							0.12	0.12	0
Other taxes on production	0.24							0.24							0.04	0.04	0
Interest																	0
Current taxes on income and wealth								0.60	0.02		0.27		0.30				0
Social contributions								0.39	0.02		0.18		0.19				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						0.80									0.80		0
Non-financial net position		0.89		0.07		-1.20		2.61		-0.21		-1.90		-0.97		0.71	0
Deposits	0.78		0.00	3.87			2.23		0.03		0.34		0.36		0.13		0
Debt	0.10		3.93			1.20	0.38			0.24		2.24		1.33	0.58		0
Financial net position		-0.89		-0.07		1.20		-2.61		0.21		1.90		0.97		-0.71	0

Use: uses, Res: resources

The NFCs and FCs are in a net lending position, mainly due to the received operating surplus. The GG-RP, and all three income household groups are in a net borrowing position because they take on loans to finance the Recovery Plan and the thermal retrofitting works, respectively.

When analyzed as a whole, i.e., when summing the change in wealth of both functions, the general government presented a significant increase in net wealth. The ROW has also benefitted from the perturbation in this first period.

Scenario Sc2.b

As with the simplified version of the perturbation, and as expected, the main differences between the first scenario and the second scenario are in the net worth of medium and high skilled households, as presented in Table 4.42.

In this scenario, low-skilled and medium-skilled present an induced consumption 13% lower than in the previous scenario, and the high-skilled income group 13% higher than in scenario Sc2.a. The new final balances differ from the previous scenario, concentrating the resources to high-skilled HHs because of the assumption of this scenario.

The other institutional sectors do not present any significant change in relation to the previous scenario.

Table 4.42 | Transaction-flow matrix at the end of first period, SC2.B

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.91							0.04		0.41		0.59			0.13	0
Gross capital formation		5.80							0.71		3.40		1.68				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.40															1.40	0
Operating surplus	1.57	0.89		0.07				0.30						0.31	0.61	0.61	0
Wages and salaries	2.44									0.10		1.12		1.22			0
Employer's social contributions	0.82							0.82									0
Taxes on products	0.27							0.27							0.12	0.12	0
Other taxes on production	0.24							0.24							0.04	0.04	0
Interest																	0
Current taxes on income and wealth								0.60	0.02		0.24		0.33				0
Social contributions								0.39	0.02		0.18		0.19				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						0.80									0.80		0
Non-financial net position		0.89		0.07		-1.20		2.61		-0.21		-1.95		-0.91		0.70	0
Deposits	0.79		-0.01	3.87			2.23		0.03		0.29		0.41		0.12		0
Debt	0.10		3.93			1.20	0.38			0.24		2.24		1.33	0.58		0
Financial net position		-0.89		-0.05		1.20		-2.61		0.21		1.95		0.91		-0.70	0

Use: uses, Res: resources

Scenario Sc2.c

In this scenario, the operating surplus is entirely saved by households, in its aggregated form. This causes a reduction of 13% in total induced consumption in a second round, when compared to the previous scenarios (in scenarios Sc2.a and Sc2.b the induced consumption was 1.04 billion and in scenario Sc2.c it is 0.91 billion, as presented in Table 4.43). With less money circulating in the second round, the resources of the government were reduced by €0.05 billion as well as the ones of NFCs and the ROW (both with reductions of €0.02 billion).

The HHs, on the other hand, had an increase in their wealth of around 3%, however, there is no distinction with regard to the proportions received by each income group.

Table 4.43 | Transaction-flow matrix at the end of first period, Sc2.c

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH		HH						ROW		Sum
											LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.79							0.91		0.04		0.41		0.46			0.12	0
Gross capital formation		5.80							5.80										0
Exports of goods and services		0.03															0.03		0
Imports of goods and services	1.39																	1.39	0
Operating surplus	1.52	0.87		0.06				0.29		0.30							0.87	0.87	0
Wages and salaries	2.39									2.39		0.10		1.10		1.20			0
Employer's social contributions	0.81							0.81											0
Taxes on products	0.27							0.27									0.12	0.12	0
Other taxes on production	0.23							0.23									0.04	0.04	0
Interest																			0
Current taxes on income and wealth								0.59	0.59		0.02		0.24		0.26				0
Social contributions								0.38	0.38		0.02		0.17		0.19				0
Social benefits other than social transfers in kind					2.00					2.00									0
Other current transfers						0.80											0.80		0
Non-financial net position		0.87		0.06		-1.20		2.56		-2.98		0.02		0.27		0.29		0.68	0
Deposits - temporary			0.91	0.91					0.91	0.91	0.04	0.04	0.41	0.41	0.46	0.46			0
Deposits - long-term	0.76			3.87			2.18		0.83		0.02		0.27		0.29		0.10		0
Loans	0.10		3.93			1.20	0.38			3.80							0.58		0
Financial net position		-0.87		-0.06		1.20		-2.56		2.98		-0.02		-0.27		-0.29		-0.68	0

Use: uses, Res: resources

4.5.3 Only residential, simplified version

Scenario Sc3.a

As discussed in Section 4.4.3, HHs receive more money than in the detailed version because of how value-added is distributed in the constructions works activity. Therefore, in this version (so also true for Sc3.b and 3.c), the multiplier effect is 1.4% higher than the one observed in the detailed version, increasing the GDP as more consumption is induced. Table 4.44 presents the TFM obtained at the end of the first period, for scenario Sc3.a.

Table 4.44 | Transaction-flow matrix at the end of first period, Sc3.a

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.91							0.05		0.61		0.39			0.15	0
Gross capital formation		5.80							1.38		3.39		1.04				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.32															1.32	0
Operating surplus	1.70	0.97		0.07				0.33		0.01		0.20		0.12	0.58	0.58	0
Wages and salaries	2.44									0.11		1.38		0.95			0
Employer's social contributions	0.82							0.82									0
Taxes on products	0.25							0.25							0.12	0.12	0
Other taxes on production	0.21							0.21							0.04	0.04	0
Interest																	0
Current taxes on income and wealth								0.60	0.03		0.34		0.23				0
Social contributions								0.39	0.02		0.22		0.15				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						0.80									0.80		0
Non-financial net position		0.97		0.07		-1.20		2.60		-0.87		-1.82		-0.38		0.64	0
Deposits	0.86		0.00	3.86			2.21		0.03		0.41		0.29		0.05		0
Debt	0.10		3.93			1.20	0.38			0.90		2.22		0.68	0.58		0
Financial net position		-0.97		-0.07		1.20		-2.60		0.87		1.82		0.38		0.64	0

Use: uses, Res: resources

Scenario Sc3.b

Table 4.45 presents the TFM obtained at the end of the first period, for scenario Sc3.b. As high-skilled households receive all the operating surplus, their change in income increases in relation to Sc3.a, while the medium-skilled HHs decrease their income, also in relation to Sc3.a. The other French institutional sectors do not present any particular change in relation to the previous scenario.

The ROW decreases the revenues as households decrease their imports in relation to the previous scenario. This happens mainly because of the consumption patterns of medium-skilled households, which reduce their consumption in relation to the previous version.

Table 4.45 | Transaction-flow matrix at the end of first period, Sc3.b

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.91							0.04		0.52		0.49			0.14	0
Gross capital formation		5.80							1.38		3.39		1.04				0
Exports of goods and services		0.03													0.03		0
Imports of goods and services	1.32															1.32	0
Operating surplus	1.70	0.97		0.07				0.33						0.34	0.57	0.57	0
Wages and salaries	2.44									0.11		1.38		0.95			0
Employer's social contributions	0.82							0.82									0
Taxes on products	0.25							0.25							0.11	0.11	0
Other taxes on production	0.21							0.21							0.04	0.04	0
Interest																	0
Current taxes on income and wealth								0.60	0.02		0.30		0.28				0
Social contributions								0.39	0.02		0.22		0.15				0
Social benefits other than social transfers in kind					2.00					0.47		1.17		0.36			0
Other current transfers						0.80									0.80		0
Non-financial net position		0.97		0.07		-1.20		2.60		-0.87		-1.88		-0.31		0.63	0
Deposits	0.86		0.00	3.86			2.22		0.03		0.34		0.37		0.04		0
Debt	0.10		3.93			1.20	0.38			0.90		2.22		0.68	0.58		0
Financial net position		-0.97		-0.07		1.20		-2.60		0.87		1.88		0.31		-0.63	0

Use: uses, Res: resources

Scenario Sc3.c

In this scenario, the induced consumption presents the lowest value when compared with the previous ones. Therefore, a lower increase in GDP is observed for Sc3.c as less induced consumption takes place in this scenario. Table 4.46 presents the TFM obtained at the end of the first period, for scenario Sc3.c.

Table 4.46 | Transaction-flow matrix at the end of first period, Sc3.c

(Billion euros)	NFC		FC		GG-RP		GG-SA		HH		HH						ROW		Sum
											LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		0.78							0.91		0.04		0.52		0.34			0.13	0
Gross capital formation		5.80							5.80		1.38		3.39		1.04				0
Exports of goods and services		0.03															0.03		0
Imports of goods and services	1.30																	1.30	0
Operating surplus	1.66	0.94		0.07				0.32		0.33							0.82	0.82	0
Wages and salaries	2.39									2.39		0.11		1.36		0.93			0
Employer's social contributions	0.80							0.80											0
Taxes on products	0.25							0.25									0.11	0.11	0
Other taxes on production	0.20							0.20									0.04	0.04	0
Interest																			0
Current taxes on income and wealth								0.59	0.59		0.02		0.29		0.20				0
Social contributions								0.38	0.38		0.02		0.21		0.15				0
Social benefits other than social transfers in kind					2.00					2.00		0.47		1.17		0.36			0
Other current transfers						0.80											0.80		0
Non-financial net position		0.94		0.07		-1.20		2.54		-2.96		-0.87		-1.90		-0.44		0.60	0
Deposits - temporary			0.91	0.91					0.91	0.91	0.04	0.04	0.52	0.52	0.34	0.34			0
Deposits - long term	0.84			3.86			2.16		0.85		0.03		0.32		0.24		0.02		0
Debt	0.10		3.93			1.20	0.38			3.80		0.90		2.22		0.68	0.58		0
Financial net position		-0.94		-0.07		1.20		-2.54		2.96		0.87		1.90		0.44		-0.60	0

Use: uses, Res: resources

4.6 Second period – monetary distribution and redistribution

In the second period, the energy savings represent the perturbation. The calculations of the monetary distribution follow the equations presented in Section 4.4, where the vector "Perturbation" is composed of the negative changes in demand for energy products and services as described in Section 4.2.1.2, p.106, for the simplified version, and Section 4.2.2.2, p.115, for the detailed version. In addition to the energy savings, which are an effect of the initial perturbation (thermal retrofitting works are conducted with the purpose of saving energy), the interest payments take place, also as a result of the financial balances from the previous period.

The interests paid by GG-RP to FCs (Int_L) and from FCs to HH (Int_D) in the current period (p) are calculated by multiplying the interest rates ($i_L$and i_D) respectively to changes in loans (L) and deposits (D) from previous period (p-1), as described in Equations 4-6 and 4-7.

$$Int_L{}^p = L^{p-1} \cdot i_L \qquad \text{Equation 4-6}$$

$$Int_D{}^p = D^{p-1} \cdot i_D \qquad \text{Equation 4-7}$$

The interest rates used in this thesis are taken from the French central bank database, and are 3.70% for loans and 2.85% for deposits. Households and non-financial corporations pay taxes concerning their income from interests (property income). For HHs, the taxes are considered to be the same rate value as the flat tax, which is 30%, 12.8% for income tax and 17.2% for social contributions. For NFCs, the tax rate applied is the corporate income tax (CIT), which depends on the overall revenue of the company. For companies with a turnover lower than €10 million, the CIT is 15%, for companies with a turnover lower than €250 million, the CIT is 26.5% and it is 27.0% otherwise (Direction Générale des Finances Publiques, 2021). In this thesis, since data for interests received is aggregated, the maximum value is used (27%).

Contrarily to the first period, where distribution and redistribution were presented in different sections to allow the reader to clearly distinguish the mechanisms associated with each process, in this section, the TFMs for distribution and redistribution will be presented in the same subsection, i.e., the TFMs of first and second rounds of second period are presented in the same section, for each scenario.

4.6.1 Total budget, simplified version

Scenario Sc1.a

The annual savings in money spent on paying energy bills are estimated to be €47.42 million, €23.22 million from GG, and €24.20 million from households, as presented in Table 4.47. These savings reduce the imports of goods and services by 12.36 million euros, the operating surplus by €14.24 million, wages and salaries by €18.35 million, and total taxes on production by €2.57 million. The interests are paid mainly by the GG-RP, which is the institutional sector the most affected in the first round of the second period of monetary distribution.

The other institutional sector in a borrowing position is the ROW since it is affected by the decrease in imports from French industries. The countries and regions the most impacted by the decrease in imports are Asia and Pacific (crude petroleum), Norway (natural gas), Middle East (crude petroleum), Africa (crude petroleum), Germany (natural gas), United Kingdom (crude petroleum), United States (crude petroleum), and Russia (crude petroleum).

Even though the GG-SA is affected by the reduction in income coming from production taxes (which present a reduction), they receive taxes on property income coming from the interest circulating in this round. Besides, the GG-SA also receives interest for depositing money at the end of the first period. The combination of these resources overtakes the decrease in revenue and assures a net lending position for the GG-SA.

The NFCs would also be in a borrowing position if they did not receive the interest from the FCs for their deposits in the previous period. However, since they were in a net lending position at the end of the first round, they receive non-negligible money regarding interests.

All three income groups of households are in a net lending position, resulting from the combination of the reduction in energy bills and the interests received from their deposits made in the first period. Finally, the main reason for FCs being in a net lending position is the difference between interest rates on deposits and loans, which is the principle of banking activity.

Table 4.47 | Transaction-flow matrix of first round, second period, Sc1.a (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-47.42			-23.22				-5.73		-14.14		-4.32				0
Gross capital formation																	0
Exports of goods and services		-0.11													-0.11		0
Imports of goods and services	-12.36															-12.36	0
Operating surplus	-14.24	-8.10		-0.59				-2.73		-0.11		-1.70		-1.00	-6.64	-6.64	0
Wages and salaries	-13.73									-0.46		-4.85		-8.43			0
Employer's social contributions	-4.62							-4.62									0
Taxes on products	-1.70							-1.70							-0.97	-0.97	0
Other taxes on production	-0.87							-0.87							-0.63	-0.63	0
Interest		17.02	73.84	115.44	115.44			38.00		0.72		8.65		9.44			0
Current taxes on income and wealth	4.60							3.41	-0.03		-0.31		-0.84				0
Social contributions								1.07	0.05		0.72		0.29				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		4.32		41.01		-92.22		32.56		5.86		15.84		4.88		-12.25	0
Deposits	4.32		41.01		-92.22		32.56		5.86		15.84		4.88		-12.25		0
Debts																	0
Financial net position		-4.32		-41.01		92.22		-32.56		-5.86		-15.84		-4.88		12.25	0

Use: uses, Res: resources

The monetary redistribution resulting from the saved money of households and from the money received from interest was calculated by applying the same alpha factors (for the savings) as in the previous period. The results at the end of the second period are presented in Table 4.48.

The induced consumption of HH represents about one third of the drop in energy consumption in the first round. All three income groups are thus in a net lending position at the end of the second period, the medium-skilled with the highest net balance.

The GG-SA and the ROW recovered, in the second round, a part of the money not earned in the first round due to the drop on energy consumption. However, at the end of the second period, they both remain in a net borrowing position. It is worth noting that even if the ROW recovers part of the money not earned in the first round, the industries and the countries benefited in the second round are not the same as the ones affected in the first round. The top 5 foreign activities that have an increase in their outputs as a result of the induced consumption are the following: Spanish hotel and restaurant services, Swiss hotel and restaurant services, chemical products from United States, Belgian hotel and restaurant services, and Belgian land transportation services.

FCs and GG-RP are not affected significantly by the second round, so the results analyzed in the first round are valid for the whole period.

Table 4.48 | Transaction-flow matrix at the end of second period, Sc1.a (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-31.90			-23.22				-1.40		-3.29		-0.95			3.03	0
Gross capital formation																	0
Exports of goods and services		-0.02													-0.02		0
Imports of goods and services	-10.87															-10.87	0
Operating surplus	-9.25	-5.26		-0.39				-1.77		-0.07		-1.11		-0.65	-4.91	-4.91	0
Wages and salaries	-8.12									-0.10		-2.30		-5.72			0
Employer's social contributions	-2.73							-2.73									0
Taxes on products	-1.23							-1.23							-0.59	-0.59	0
Other taxes on production	-0.19							-0.19							-0.54	-0.54	0
Interest		17.02	73.84	115.44	115.44			38.00		0.72		8.65		9.44			0
Current taxes on income and wealth	4.60							4.84	0.05		0.37		-0.18				0
Social contributions								1.95	0.11		1.13		0.72				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		7.64		41.21		-92.22		38.88		1.78		7.05		3.48		-7.82	0
Deposits	7.64		41.01	-0.21	-92.22		38.88		1.78		7.05		3.48		-7.82		0
Debt																	0
Financial net position		-7.64		-41.21		92.22		-38.88		-1.78		-7.05		-3.48		7.82	0

Use: uses, Res: resources

Scenario Sc1.b

For scenarios Sc1.b and Sc1.c, the results are presented only for the balance at the end of the second period. The results for scenario Sc1.b are presented in Table 4.49. When compared to the results presented in Table 4.48, there is no significant difference, because the operating surplus does not represent a major source of income for households, and so its significance in driving the induced consumption is not weighty. However, some differences may be pointed out.

In the scenario Sc1.b, all income groups are in a net lending position, as well as in the previous scenario, with no significant effect observed for concentrating the operating surplus to high-skilled households. The latter is indeed the group the most affected by the decrease in revenue resulting from the avoided energy consumption. However, they also have a lower consumption in the second round, as they resources are lower in scenario Sc1.b, resulting thus in similar balances at the end. Moreover, the relative significance of interests also contributes for keeping all three income groups in a net lending position at the end of the second period.

The results for the other institutional sectors are not significantly affected by the assumption of concentrating the operating surplus on high-skilled HHs.

Table 4.49 | Transaction-flow matrix at the end of second period, Sc1.b (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-31.98			-23.22				-1.33		-2.38		-1.94			3.11	0
Gross capital formation																	0
Exports of goods and services		-0.02													-0.02		0
Imports of goods and services	-10.82															-10.82	0
Operating surplus	-9.13	-5.19		-0.38				-1.75						-1.81	-4.83	-4.83	0
Wages and salaries	-7.97									-0.09		-2.23		-5.65			0
Employer's social contributions	-2.68							-2.68									0
Taxes on products	-1.22							-1.22							-0.57	-0.57	0
Other taxes on production	-0.17							-0.17							-0.53	-0.53	0
Interest		17.02	73.84	115.44	115.44			38.00		0.72		8.65		9.44			0
Current taxes on income and wealth	4.60							4.88	0.07		0.62		-0.41				0
Social contributions								1.98	0.11		1.14		0.73				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		7.23		41.22		-92.22		39.04		1.78		7.04		3.60		-7.69	0
Deposits	7.23			-41.22	-92.22		39.04		1.78		7.04		3.60		-7.69		0
Debt																	0
Financial net position		-7.23		-41.22		92.22		-39.04		-1.78		-7.04		-3.60		7.69	0

Use: uses, Res: resources

Scenario Sc1.c

In this scenario, the second round (monetary redistribution) is less significant than the in the previous scenarios. This happens because all property income (operating surplus and interests) generated in the first round of second period is saved by HH. As observed in the previous scenarios, the interests received by HHs play a key role in their income and, as a consequence, in the temporary net wealth at the end of the first round of the second period. Therefore, assuming that all interests are saved reduces significantly the money circulating in the second round of the second period. Table 4.50 presents the TFM at the end of the second period for this scenario.

The induced consumption of this scenario is the lowest one, with €10.99 million of total expenditure on consumption goods and services. This affects all institutional sectors, presenting the lowest values of changes in net wealth when compared to scenarios Sc1.a and SC1.B.

In the previous scenarios, all three income groups of HHs were in a net lending position at the end of the second period. In this scenario, it is not possible to do such an analysis since the property income is accounted for in an aggregated form. Therefore, we can only compare

the overall change in net wealth of HHs as whole, which, in this scenario is 63% higher than in both scenarios Sc1.a and Sc1.b.

Other institutional sector particularly affected by the decrease in induced consumption are the GG-SA, which receive less money from taxes on products and on income, and the ROW. The latter receives less money from induced importing of products and services by HHs and also less money from inter-industry importing.

Table 4.50 | Transaction-flow matrix at the end of second period, Sc1.c (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH		HH						ROW		Sum
											LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-38.48			-23.22				-13.21		-1.70		-6.53		-4.97			2.05	0
Gross capital formation																			0
Exports of goods and services		-0.05															-0.05		0
Imports of goods and services	-11.42																	-11.42	0
Operating surplus	-11.31	-6.43		-0.47				-2.17		-2.24							-5.47	-5.47	0
Wages and salaries	-10.40									-10.40		-0.25		-3.34		-6.81			0
Employer's social contributions	-3.50							-3.50											0
Taxes on products	-1.41							-1.41									-0.72	-0.72	0
Other taxes on production	-0.49							-0.49									-0.57	-0.57	0
Interest		17.02	76.67	115.44	115.44			38.00		21.64									0
Current taxes on income and wealth	4.60							4.62	0.03		-0.05		-0.73		-1.48				0
Social contributions								2.08	2.08		-0.04		-0.53		-1.08				0
Social benefits other than social transfers in kind																			0
Other current transfers																			0
Non-financial net position		5.99		38.30		-92.22		37.14		20.10		1.55		4.44		0.72		-9.32	0
Deposits - temporary				5.02					2.08		0.13		0.94		1.01		2.93		0
Deposits - long term	5.99			-43.32	-92.22		37.14		18.02		1.42		3.50		-0.29		-12.25		0
Debts																			0
Financial net position		-5.99		-38.30		92.22		-37.14		-20.10		-1.55		-4.44		-0.72		9.32	0

Use: uses, Res: resources

4.6.2 Only residential, detailed version

Scenario Sc2.a

In the detailed version, the perturbation for the second period is a reduction of €174.1 million in French energy activities. This reduction causes a decrease in value-added, reducing the money distributed to other institutional sectors, as presented in Table 4.51.

Non-financial corporations, FCs, GG-SA and HHs are a in a net lending position at the end of the first round of the second period. For NFCs, it happens due to the interest received from depositing money in the first period. One part of this money goes to GG-SA in form of

taxes. The latter is also in a net lending position because, as well as NFCs, they receive interest for depositing money in the previous period, but also because of the taxes on the interest paid by HHs and NFCs. The main reason for HHs being in a net positive balance is mainly that they save money from energy bills. However, for the high-skilled income group, the interest received also plays a key role in their income. Finally, the FCs are in a lending position because of the difference in interest rates on deposits and on loans.

The GG-RP and the ROW are in a net borrowing position. GG-RP pays for the interest on loans taken out to finance the Recovery Plan, from government and households. This is because the latter, when taking out interest-free loans, does not pay for the interest; it is actually the government who pays it for them.

Moreover, the ROW is in a net borrowing position because of the money that they do not receive from imports made by French economic activities. The most affected countries and regions are Asia and Pacific (crude petroleum), the Middle East (crude petroleum), Africa (crude petroleum), Norway (natural gas), the United Kingdom (crude petroleum), Germany (natural gas), the United States (crude petroleum), and Russia (crude petroleum).

Table 4.51 | Transaction-flow matrix of first round, second period, Sc2.a (MEUR)

(Million euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-174.1							-41.3		-101.8		-31.1				0
Gross capital formation																	0
Exports of goods and services		-0.7													-0.7		0
Imports of goods and services	-111.6															-111.6	0
Operating surplus	-36.6	-20.8		-1.5				-7.0		-0.3		-3.3		-3.6	-63.0	-63.0	0
Wages and salaries	-28.3									-1.0		-6.6		-20.8			0
Employer's social contributions	-9.5							-9.5									0
Taxes on products	-6.2							-6.2							-9.9	-9.9	0
Other taxes on production	-1.2							-1.2							-7.7	-7.7	0
Interest		22.4	106.8	185.1	185.1			63.6		0.8		8.2		11.8			0
Current taxes on income and wealth	6.1							1.0	-0.2		-1.1		-3.8				0
Social contributions								-0.9	0.0		0.4		-1.3				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		14.1		76.7		-185.1		39.9		41.0		100.8		23.5		-110.9	0
Deposits	14.1		76.7		-185.1		39.9		41.0		100.8		23.5		-110.9		0
Debt																	0
Financial net position		-14.1		-76.7		185.1		-39.9		-41.0		-100.8		-23.5		110.9	0

Use: uses, Res: resources

The temporary deposited money of the three income groups generates a second round of monetary redistribution corresponding to the induced consumption. The results of the TFM at the end of the second period are presented in Table 4.52. In this scenario, the induced consumption is an increase in final consumption expenditure of €102.05 million (€186.62 (Table 4.51) million minus €84.57 million (Table 4.52)).

Table 4.52 | Transaction-flow matrix at the end of second period, Sc2.a (MEUR)

(Million euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-77.9							-11.0		-32.7		-14.9			19.4	0
Gross capital formation																	0
Exports of goods and services		0.0													0.0		0
Imports of goods and services	-101.2															-101.2	0
Operating surplus	-1.9	-1.1		-0.1				-0.4		0.0		-0.2		-0.2	-51.0	-51.0	0
Wages and salaries	10.7									1.5		11.2		-2.0			0
Employer's social contributions	3.6							3.6									0
Taxes on products	-2.9							-2.9							-7.3	-7.3	0
Other taxes on production	3.6							3.6							-7.1	-7.1	0
Interest		22.4	106.8	185.1	185.1			63.6		0.8		8.2		11.8			0
Current taxes on income and wealth	6.1							10.9	0.4		3.4		1.0				0
Social contributions								5.3	0.4		3.2		1.7				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		25.5		78.2		-185.1		83.8		12.4		45.3		21.7		-81.8	0
Deposits	25.5		76.7	-1.4	-185.1		83.8		12.4		45.3		21.7		-81.8		0
Debt																	0
Financial net position		-25.5		-78.2		185.1		-83.8		-12.4		-45.3		-21.7		81.8	0

Use: uses, Res: resources

The second round of monetary distribution mostly affects the NFCs, the GG-SA, HHs, and the ROW. Non-financial corporations receive money from operating surplus at almost the same amount as they had received in interest in the first round of the second period. The money received by GG-SA in the second round is also equivalent to the amount received in the first round.

High-skilled HHs present the lowest temporary change in net worth in the first round of the second period (2P1R) (see Table 4.52); however, they are in the second position at the end of the second period (see Table 4.52). This happens because they have benefitted from the monetary distribution in the second round, not being the drivers of the consumption but receiving money from the economic activities affected by the induced consumption.

Finally, the ROW recovers a part of the money not earned in the first round, as imports from French households and from French economic activities resulting from the induced consumption. Their balance in the second round is positive, however, the countries and the activities that are mostly affected are not the same as the ones negatively impacted in the first round. Some examples of the mostly positively impacted activities are the Spanish hotel and restaurant services, chemical products from the United States, Swiss and Belgian hotel and restaurant services, Belgian transportation services, and German food products.

Scenario Sc2.b

The overall results of this scenario do not change significantly from the previous results presented in Table 4.52. This because the relative importance of the operating surplus in relation to other sources of income is low, as also observed in the simplified version. The TFM at the end of the second period is presented in Table 4.53.

Table 4.53 | Transaction-flow matrix at the end of second period, Sc2.b (MEUR)

(Million euros)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-78.1							-10.8		-30.9		-16.8			19.5	0
Gross capital formation																	0
Exports of goods and services		-0.1													-0.1		0
Imports of goods and services	-102.0															-102.0	0
Operating surplus	-4.8	-2.7		-0.2				-0.9						-1.0	-51.7	-51.7	0
Wages and salaries	7.5									1.3		9.7		-3.5			0
Employer's social contributions	2.5							2.5									0
Taxes on products	-3.1							-3.1							-7.5	-7.5	0
Other taxes on production	3.2							3.2							-7.1	-7.1	0
Interest		22.4	106.8	185.1	185.1			63.6		0.8		8.2		11.8			0
Current taxes on income and wealth	6.1							10.1	0.4		3.2		0.5				0
Social contributions								4.8	0.3		2.9		1.5				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		32.2		78.1		-185.1		80.2		12.1		42.7		22.1		-82.3	0
Deposits	32.2			-78.1	-185.1		80.2		12.1		42.7		22.1		-82.3		0
Debt																	0
Financial net position		-32.2		-78.1		185.1		-80.2		-12.1		-42.7		-22.1		82.3	0

Use: uses, Res: resources

The major difference in relation to the previous scenario lies in the change in net wealth of the three income groups, mainly medium- and high-skilled HHs. This happens because the high-skilled HHs receive all the operating surplus and, thus, are the most affected by the

reduction in value-added in the first round, which is not compensated by the operating surplus created in the induced consumption.

Medium-skilled HHs consume more in Sc2.b than in Sc2.a, because they are not impacted by the reduction in resources coming from operating surplus in the first round, that being the reason for their decrease in net wealth when compared to Sc2.a. The opposite happens to high-skilled HHs, as previously explained.

Scenario Sc2.c

The results of the monetary distribution and redistribution for the second period, for the scenario Sc2.c, are presented in Table 4.54. As less money circulates in the second round, all institutional sectors receive less money than in the previous scenarios. When compared to scenario Sc2.b, the reductions in net worth are 5% for NFCs, 4% for the GG-SA, and 2% for the ROW. When analyzed in its aggregated form, the HHs increase their wealth by 5% in relation to the previous scenario.

Table 4.54 | Transaction-flow matrix at the end of second period, Sc2.c (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH		HH						ROW		Sum
											LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-83.3							-64.6		-11.2		-34.9		-18.6			18.6	0
Gross capital formation																			0
Exports of goods and services		-0.1															-0.1		0
Imports of goods and services	-102.4																	-102.4	0
Operating surplus	-6.6	-3.7		-0.3				-1.3		-1.3							-52.2	-52.2	0
Wages and salaries	5.6									5.6		1.2		8.8		-4.4			0
Employer's social contributions	1.9							1.9											0
Taxes on products	-3.3							-3.3									-7.6	-7.6	0
Other taxes on production	2.9							2.9									-7.1	-7.1	0
Interest		21.7	107.5	185.1	185.1			62.2		23.6									0
Current taxes on income and wealth	5.9							9.8	3.9		0.3		1.9		-1.0				0
Social contributions								4.9	4.9		0.2		1.4		-0.7				0
Social benefits other than social transfers in kind																			0
Other current transfers																			0
Non-financial net position		30.7		77.3		-185.1		77.2		83.6		11.9		40.4		15.8		-83.7	0
Deposits - temporary				48.4					21.2		1.3		9.6		10.2		27.2		0
Deposits - long term	30.7			-125.7	-185.1		77.2		62.4		10.6		30.8		5.6		-110.9		0
Debts																			0
Financial net position		-30.7		-77.3		185.1		-77.2		-83.6		-11.9		-40.4		-15.8		83.7	0

Use: uses, Res: resources

4.6.3 Only residential, simplified version

Scenario Sc3.a

This version considers the energy savings of residential buildings from the simplified version, i.e., households save €0.070 billion (or €70 million) by year. This reduction in energy bills is composed of €16.6 million for low-skilled HHs, €41.0 million for medium-skilled HHs and €12.5 million for high-skilled HHs, as presented in Table 4.55.

Table 4.55 | Transaction-flow matrix of first round, second period, Sc3.a (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-70.2							-16.6		-41.0		-12.5				0
Gross capital formation																	0
Exports of goods and services		-0.2													-0.2		0
Imports of goods and services	-16.8															-16.8	0
Operating surplus	-20.9	-11.9		-0.9				-4.0		-0.2		-2.5		-1.5	-8.8	-8.8	0
Wages and salaries	-21.5									-0.7		-7.9		-12.9			0
Employer's social contributions	-7.2							-7.2									0
Taxes on products	-2.5							-2.5							-1.3	-1.3	0
Other taxes on production	-1.4							-1.4							-0.8	-0.8	0
Interest		24.6	108.8	44.4	44.4			63.2		0.8		9.7		10.5			0
Current taxes on income and wealth	6.7							3.8	-0.1		-1.0		-1.8				0
Social contributions								0.2	0.0		0.4		-0.2				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		6.1		-65.3		-44.4		52.0		16.6		40.9		10.7		-16.6	0
Deposits	6.1		-65.3		-44.4		52.0		16.6		40.9		10.7		-16.6		0
Debts																	0
Financial net position		-6.1		65.3		44.4		-52.0		-16.6		-40.9		-10.7		16.6	0

Use: uses, Res: resources

As they decrease their spending on energy, the assumption is that they have a temporary increase in wealth, which also induces consumption. The results of the second period are presented in Table 4.56.

Table 4.56 | Transaction-flow matrix at the end of second period, Sc3.a (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-30.4							-4.3		-13.0		-5.1			7.9	0
Gross capital formation																	0
Exports of goods and services		0.1													0.1		0
Imports of goods and services	-12.8															-12.8	0
Operating surplus	-7.7	-4.4		-0.3				-1.5		-0.1		-0.9		-0.5	-4.2	-4.2	0
Wages and salaries	-6.7									0.2		-1.2		-5.7			0
Employer's social contributions	-2.3							-2.3									0
Taxes on products	-1.3							-1.3							-0.3	-0.3	0
Other taxes on production	0.4							0.4							-0.6	-0.6	0
Interest		24.6	108.8	44.4	44.4			63.2		0.8		9.7		10.5			0
Current taxes on income and wealth	6.7							7.6	0.1		0.8		0.0				0
Social contributions								2.6	0.2		1.5		0.9				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		13.6		-64.8		-44.4		68.7		5.0		18.3		8.5		-5.0	0
Deposits	13.6		-65.3	-0.5	-44.4		68.7		5.0		18.3		8.5		-5.0		0
Debts																	0
Financial net position		-13.6		64.8		44.4		-68.7		-5.0		-18.3		-8.5		5.0	0

Use: uses, Res: resources

When comparing Table 4.55 and Table 4.56, the influence of the second round is evident. The induced consumption compensates part of the money not received by NFCs for the drop in energy product sales. NFCs are thus in a net lending position because of the induced consumption and the interests received. Financial corporations, on the other hand, are in a net borrowing position as they pay more interests that they receive. The GG is in a net lending position, when combining both functions, I.e., they receive more resources than they pay in interests on loans taken on the first period.

Households are all in net lending position because they receive interests and decrease their energy consumption. Moreover, the ROW is in a net borrowing position principally because of the decrease in imports in the first round of the second period.

Scenario Sc3.b

The results of the second period, for scenario Sc3.b, are presented in Table 4.57. High-skilled HHs are the only ones affected by not receiving the operating surplus that would be received in case of usual energy consumption. Therefore, they have a lower increase in net worth when compared with the other two income groups. The ROW has an increase in

resources because of higher imports from HHs, which is a combination of higher consumption of low-skilled and medium-skilled households.

Table 4.57 | Transaction-flow matrix at the end of second period, Sc3.b (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH						ROW		Sum
									LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-30.6							-4.2		-11.7		-6.6			8.0	0
Gross capital formation																	0
Exports of goods and services		0.1													0.1		0
Imports of goods and services	-12.8															-12.8	0
Operating surplus	-7.8	-4.4		-0.3				-1.5						-1.5	-4.2	-4.2	0
Wages and salaries	-6.7									0.2		-1.2		-5.7			0
Employer's social contributions	-2.3							-2.3									0
Taxes on products	-1.3							-1.3							-0.3	-0.3	0
Other taxes on production	0.4							0.4							-0.6	-0.6	0
Interest		24.6	108.8	44.4	44.4			63.2		0.8		9.7		10.5			0
Current taxes on income and wealth	6.7							7.5	0.2		1.0		-0.2				0
Social contributions								2.5	0.2		1.5		0.9				0
Social benefits other than social transfers in kind																	0
Other current transfers																	0
Non-financial net position		13.6		-64.8		-44.4		68.7		4.9		17.7		9.2		-4.8	0
Deposits	13.6			64.8	-44.4		68.7		4.9		17.7		9.2		-4.8		0
Debts																	0
Financial net position		-13.6		64.8		44.4		-68.7		-4.9		-17.7		-9.2		4.8	0

Use: uses, Res: resources

Scenario Sc3.c

In this scenario, the induced consumption is the lowest one when compared with Sc3.a and Sc3.b. This is because the interests are received by HHs in its aggregated form and do not compose the income that induces consumption, as in previous versions. Therefore, all institutional sectors are affected. While HHs increase their net worth by 26% in relation to previous scenarios, NFCs decrease it by 10% and the ROW by 32%.

Table 4.58 | Transaction-flow matrix at the end of second period, Sc3.c (MEUR)

(MEUR)	NFC		FC		GG-RP		GG-SA		HH		HH						ROW		Sum
											LS		MS		HS				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Final consumption expenditure		-37.3							-30.4		-4.7		-16.3		-9.4			6.9	0
Gross capital formation																			0
Exports of goods and services		0.0															0.0		0
Imports of goods and services	-13.4																	-13.4	0
Operating surplus	-10.0	-5.7		-0.4				-1.9		-2.0							-4.8	-4.8	0
Wages and salaries	-9.3									-9.3		0.1		-2.4		-7.0			0
Employer's social contributions	-3.1							-3.1											0
Taxes on products	-1.5							-1.5									-0.4	-0.4	0
Other taxes on production	0.0							0.0									-0.6	-0.6	0
Interest		24.6	112.0	44.4	44.4			63.2		24.1									0
Current taxes on income and wealth	6.7							7.3	0.6		0.0		-0.5		-1.5				0
Social contributions								2.7	2.7		0.0		-0.4		-1.1				0
Social benefits other than social transfers in kind																			0
Other current transfers																			0
Non-financial net position		12.3		-68.0		-44.4		66.7		40.0		4.7		14.8		5.1		-6.6	0
Deposits - temporary				17.7					7.7		0.5		3.5		3.7		10.1		0
Deposits - long term	12.3			50.3	-44.4		66.7		32.3		4.2		11.4		1.4		-16.6		0
Debts																			0
Financial net position		-12.3		68.0		44.4		-66.7		-40.0		-4.7		-14.8		-5.1		6.6	0

4.7 Conclusions

This chapter presented how the method proposed in the thesis (Chapter 3) can be applied to a public policy in the construction sector. In the case of the thesis it is the French Recovery Plan, notably the money dedicated to expand massively thermal retrofitting works in existing buildings. Three options for characterizing the perturbation were studied. The first version, called "total budget, simplified version", considered a simplified perturbation where the money from Recovery Plan to foster thermal retrofits in public buildings (€3.0 billion) and residential buildings (€2.0 billion) was studied. For that, some assumptions were made and two are highlighted here. The first assumption is that all money spent by households comes from the recovery plan, meaning that they receive and spend €2.0 billion in thermal retrofitting services. The second assumption simplifies the modelling of the exogenous perturbation by considering that the affected economic activity is the French construction works. In this

version, there is no information concerning the typology of the retrofitting works, for example, if there is an increase in demand for heat pumps or insulation material.

The second version of the perturbation is called "only residential, detailed version". The 'only residential' part of the version name is because it focuses on the budget of the plan dedicated to residential buildings, i.e., € 2.0 billion. For quantifying the thermal retrofitting works that are fostered by the plan, an econometric model called MENFIS was used. According to MENFIS simulations, an increase in 2.0 billion in financial aid (mainly through the primes called MaPrimeRénov), creates an actual rise in demand for thermal retrofitting works of around €5.80 billion. The assumption made in this detailed version was that the money used to complement the needed budget comes from the wealth of households, either from their own current accounts or from loans, which are encouraged by free-interest loan measures dedicated to thermal retrofitting. The latter was analyzed in the results. The energy savings occurring as a result of the increase in energy efficiency from the second period onwards were also characterized by using MENFIS simulations. The results showed that the energy savings cover one part of households debt, while induces consumption in a second round.

The third version studied by the thesis combines elements from the two previous versions. It is called "only residential, simplified version", because it focuses on residential buildings, i.e., € 2.0 billion; however, different from the previous version, it considers that only "construction works" are affected in the foreground. For comparison purposes, the same expenditure was considered in the version, meaning that the recovery plan covers only one part of the total expenditure (€5.80 billion).

For each version, three scenarios were studied to consider the payment of operating surplus. The first scenario (a) considers that the operating surplus of each activity is distributed to the three income groups by using the same proportions as the wages and salaries. The second scenario (b) considered that all operating surplus is received by the high-skilled households. In the third scenario (c), the three income groups are aggregated for receiving operating surplus and interests. They are disaggregated when accounting for the resources and uses that are disaggregated already in EXIOBASE.

When comparing the global results of the three versions, both simplified versions (total budget and only residential buildings) have the same multiplier factor, mainly because of the monetary distribution of the value-added of construction works. This multiplier factor is higher than the one observed for the detailed version, meaning that less money circulates in the second round for the latter, with a lower increase in GDP.

When comparing the three scenarios (a, b and c), we observe the same patterns for the three versions. Scenarios 'a' and 'b' have similar values in induced consumption, which are higher than scenarios 'c'. However, the latter present the highest values of total household net wealth.

5

Method applied to the case study: environmental and socio-economic consequences

This chapter presents the results for three environmental impact categories and discusses a few socio-economic aspects resulting from the model developed in this thesis. From the environmental point of view, GHG emissions, wastes production and energy consumption are assessed, which are, currently, the key environmental issues for the sector. A sensitivity analysis was also conducted for GHG emissions and is presented in Section 5.2. The choice for this impact category to compare the results by changing the dataset was made because, among the three categories, GHG emissions are the only ones that can be consistently obtained from all datasets, since emissions of substances are included in all of them.

The socio-economic issues studied here concern the pure redistributive effects, i.e., how the monetary (re)distribution affects the stocks of the institutional sectors, with a focus on changes in net wealth of households, general government, financial and non-financial corporations. In addition, the marginal utility of the French Recovery Plan is also assessed, as well as the changes in trade for key trade partners of France. All impacts are evaluated for three scenarios of operating surplus distribution and three levels of detail of the economic perturbation.

The results are presented for the three versions of the exogenous perturbation, each version presenting the three scenarios for distributing the operating surplus to households. The scenarios were described in Chapter 4, however, they are presented in Figure 5.1 as a reminder.

		Operating surplus		
		Option a	Option b	Option c
		Payment of operating surplus to the three income groups in each activity following the proportions of wages and salaries	Payment of operating surplus to high-skilled households	Operating surplus is received by households (aggregated) and all money is saved
Total budget (Public buildings, Houses, Apartments)	**Simplified**	**Sc1.a**	**Sc1.b**	**Sc1.c**
Only residential buildings (Houses, Apartments)	**Detailed**	**Sc2.a**	**Sc2.b**	**Sc2.c**
	Simplified	**Sc3.a**	**Sc3.b**	**Sc3.c**

Figure 5.1 | Illustration of the nine scenarios studied in the thesis

5.1 Environmental consequences

As explained in Section 3.4, the environmental impact assessed in this thesis is the **greenhouse gas (GHG) emissions**, and the additional flows within the technosphere are the **amounts of waste generated** and the **energy consumption**. Figure 5.2 presents, as a reminder, the system boundaries of the perturbations occurring in the first period (increase in demand for thermal retrofitting works) and in the second period (energy savings resulting from the increase in energy efficiency).

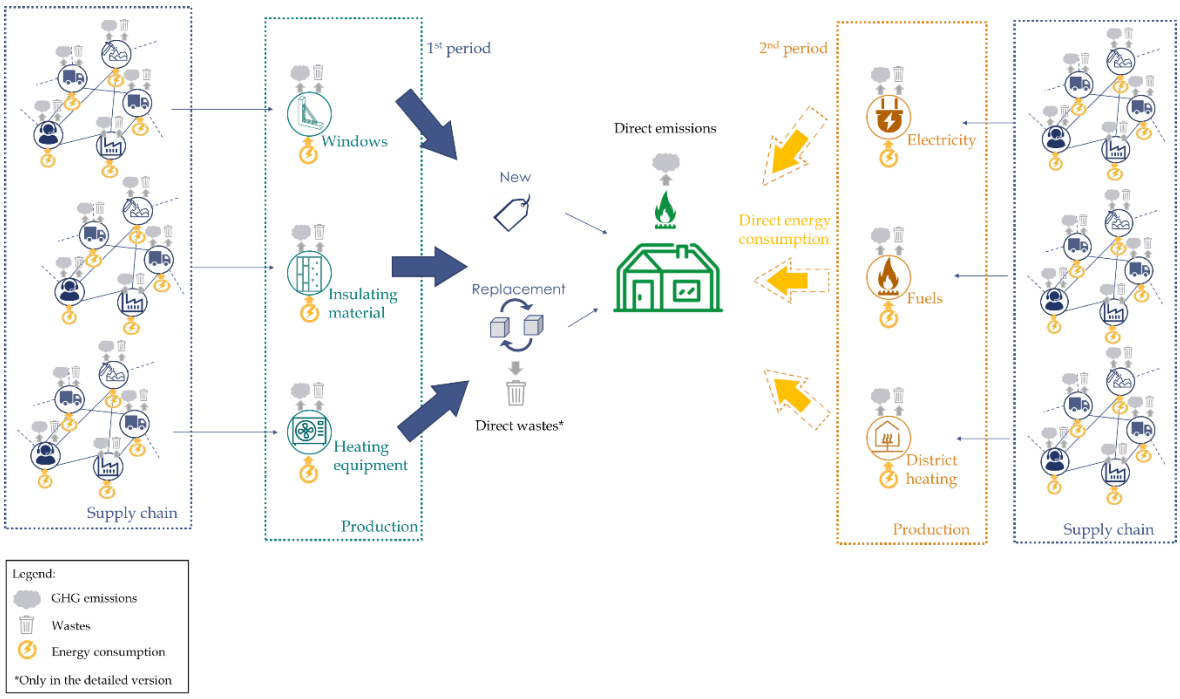


Figure 5.2 | System boundaries of the first period (left side) and the second period (right side)

In the first period, the GHG emissions are accounted for the production of efficient heating equipment, insulating materials (for walls, roofs, windows), and the entire supply chain affected by this increase in demand. In the second period, the energy savings take place; therefore, the decrease in demand for energy products represents the perturbation. The GHG emissions associated with the drop in energy consumption are the sum of the **avoided direct combustion of fuels**, the **avoided emissions from the decrease in the production of energy product**s (fuels, electricity and district heating), and also the **entire supply chain** affected by the reduction in demand. The same rationale is applied to the other environmental indicators.

In the simplified version of the case study, the production of all efficient equipment and products, by typology, is not included. Instead, it is considered that the 'construction work' in its general aggregated form is the one responding to the increase in demand for retrofitting works.

On the other hand, in the detailed version of the case study, the perturbation is specified in order to identify the industries better responding to the increase in demand for retrofitting works. With a better quantification of the equipment and construction products affected by the new policy, the amount of replaced products and equipment can be obtained, representing the direct wastes generated by the policy.

5.1.1 GHG emissions

5.1.1.1 Total budget, simplified version

The GHG emissions of each round are presented in Table 5.1, as a sum of the ones occurring in France (FR) and in the rest of the world (ROW) for the three scenarios (Sc1.a, Sc1.b and Sc1.c). The first round of the first period (1P1R) causes an increase in GHG emissions of 1,074,582 tons of CO_2e, which is the same for the three scenarios. In the second round of the first period (1P2R), scenario Sc1.a presents the highest emissions, while, as expected, scenario Sc1.c presents the lowest ones. Then, there is a drop in emissions from the energy savings (2P1R) in the second period, followed by a slight increase due to induced consumption (2P2R).

Table 5.1 | Total GHG emissions, round-by-round, total budget, simplified version (tCO2eq)

	1P1R	1P2R	1P		2P1R	2P2R		2P
Sc1.a	1 074 582	251 189	1 325 771	-	137 247	5 206	-	132 041
Sc1.b	1 074 582	245 405	1 319 987	-	137 247	5 411	-	131 837
Sc1.c	1 074 582	215 579	1 290 161	-	137 247	3 414	-	133 833

The cumulated emissions, round-by round, are illustrated in Figure 5.3. It is possible to identify the part of the emissions occurring in France and those in the rest of the world (ROW), resulting from the foreign economic activities that are indirectly affected by the change in demand caused by the Recovery Plan in France. For example, the emissions during the 1P1R

in France are 0.413 MtCO2e, while in the ROW they are 0.662 $MtCO_2e$, around 60% of the total increase. Globally, the results of the three scenarios are similar, with slight differences.

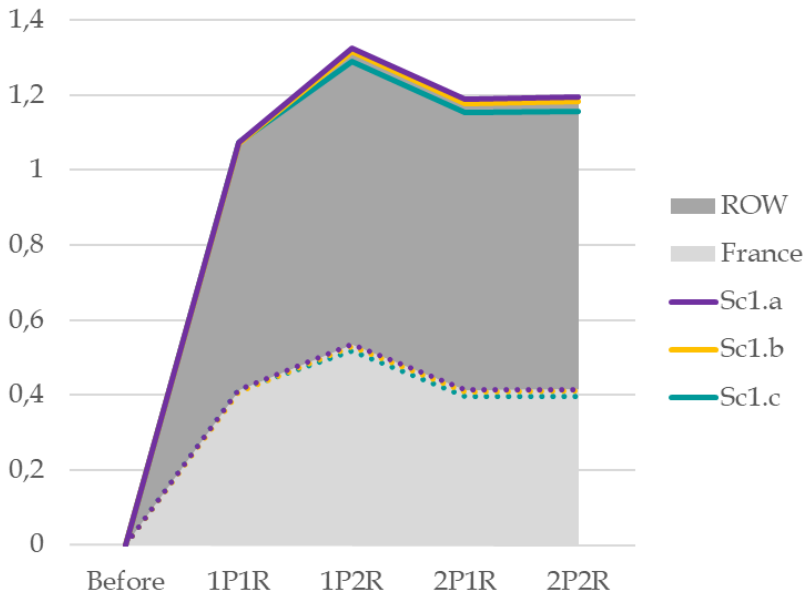


Figure 5.3 | Cumulated GHG emissions, round by round, total budget, simplified version ($MtCO_2e$)

As discussed in Section 1.1, p.11, the annual GHG emissions of residential and tertiary buildings in France are around 75 $MtCO_2e$. The part of emissions occurring in France due to the increase in demand for thermal retrofitting works (only the first-order effects, or 1P1R) are 0.413 $MtCO_2e$, representing 0.55% of total emissions of the sector in France.

As observed in Figure 5.3, the increase in emissions occurring due to the first distribution round of the first period is more expressive in the ROW (0.662 $MtCO_2e$ in the ROW *versus* 0.413 $MtCO_2e$ in France). The countries contributing the most to this increase are China (CN) (15% of ROW emissions), Germany (DE) (8% of ROW emissions), Spain (ES) (5% of ROW emissions), Russia (RU) (5% of ROW emissions), Poland (PL) (4% of ROW emissions), India (IN) (3% of ROW emissions), Italy (IT) (3% of ROW emissions), United States (US) (3% of ROW emissions), Belgium (3% of ROW emissions) and Turkey (2% of ROW emissions), as presented in Figure 5.4. In the Figure, the emissions in the aggregated regions, i.e. rest of Asia and Pacific (WA), rest of Americas (WL), rest of Europe (WE), rest of Africa (WF) and rest of the Middle East (WM), are not presented for illustrative purposes. Yet, the WA and the WF each represent around 10% of the ROW emissions.

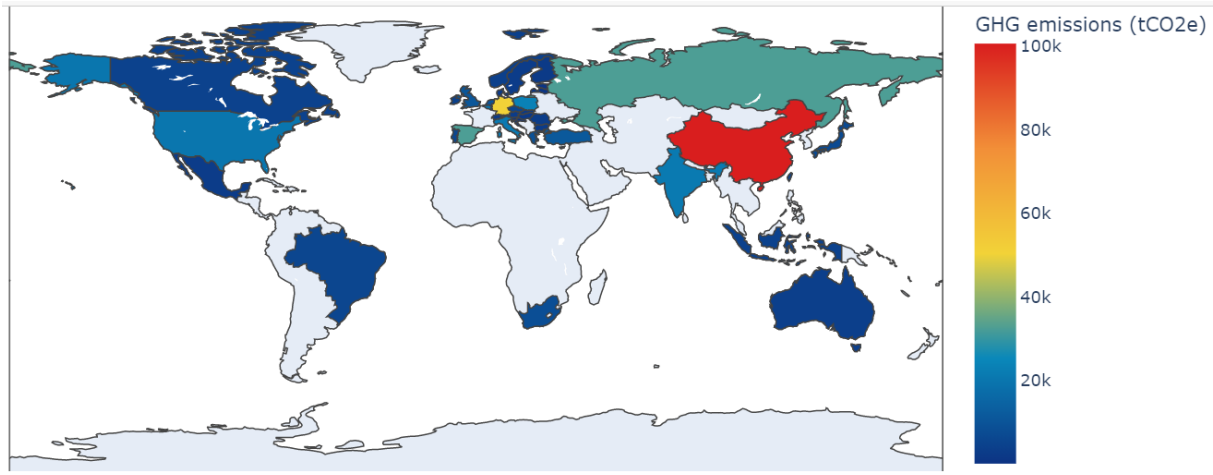


Figure 5.4 | Global emissions in the ROW, first round of the first period, total budget, simplified version (tCO_2e)

The top 10 activities (French and foreign) contributing to total emissions of the first round of the first period are presented in Figure 5.5.

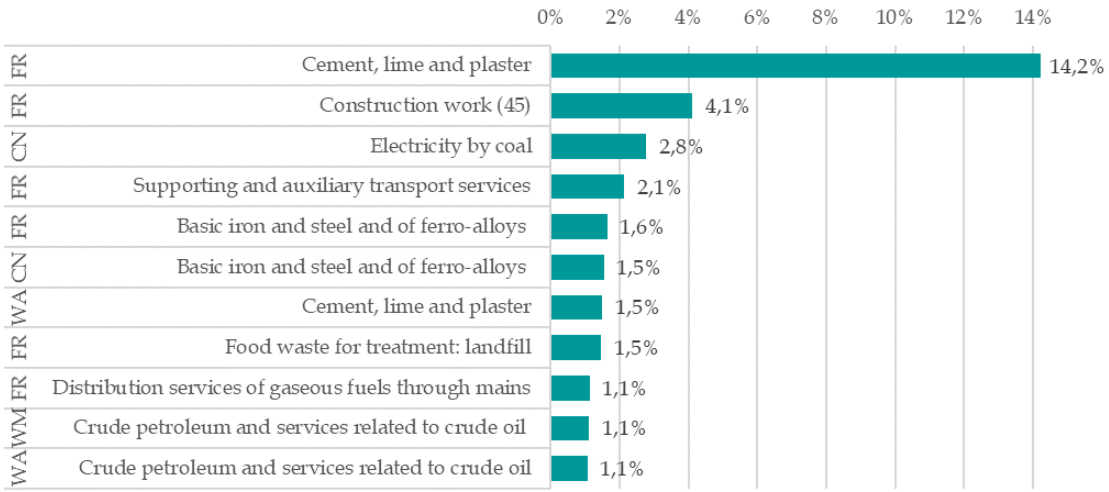


Figure 5.5 | Contribution of activities to total emissions in the first round, first period, total budget, simplified version

Because the only activity affected by the perturbation was the French 'construction work', the cement, lime and plaster products contribute the most to total GHG emissions (14.2% of total emissions). This result is not expected as the thermal retrofitting works would not necessarily increase the demand for cement. However, the cement industry is also affected as a background process being an input for construction activities in other countries and for distributing gas (building distribution structures). On the other hand, these activities are impacted by the recovery plan, directly or indirectly. To better understand these relationships, the changes in total outputs of the twenty most affected regions and countries other than France occurring as a result of the perturbation are presented in Figure 5.6.

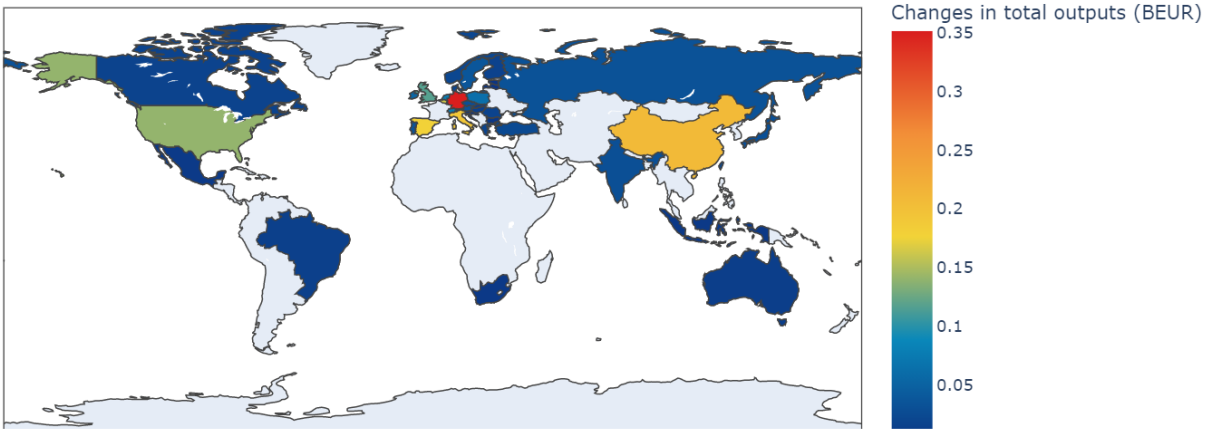


Figure 5.6 | Changes in total output, total budget, simplified version (BEUR)

The most affected country is Germany, with an increase of €0.35 billion of their total outputs. However, as the emissions of the affected products are relatively lower than other affected products, German activities do not appear in the top 10 activities contributing to GHG emissions of the first round of the first period.

China appears in the second position with an increase of €0.21 billion in total outputs to respond to the increase in demand for construction works in France. The "electricity by coal" is the 16th Chinese activity with the highest increase in total outputs, which, combined with its high GHG emission coefficient results in a relative high contribution to total GHG emissions observed in Figure 5.5.

Concerning the second round of the first period, half of emissions occur in France and the other half occur in the ROW. The most affected countries are presented in Figure 5.7. The rest of the regions are not presented for illustrative purposes. China, Germany, India, Spain and the United States appear in the top 5 countries.

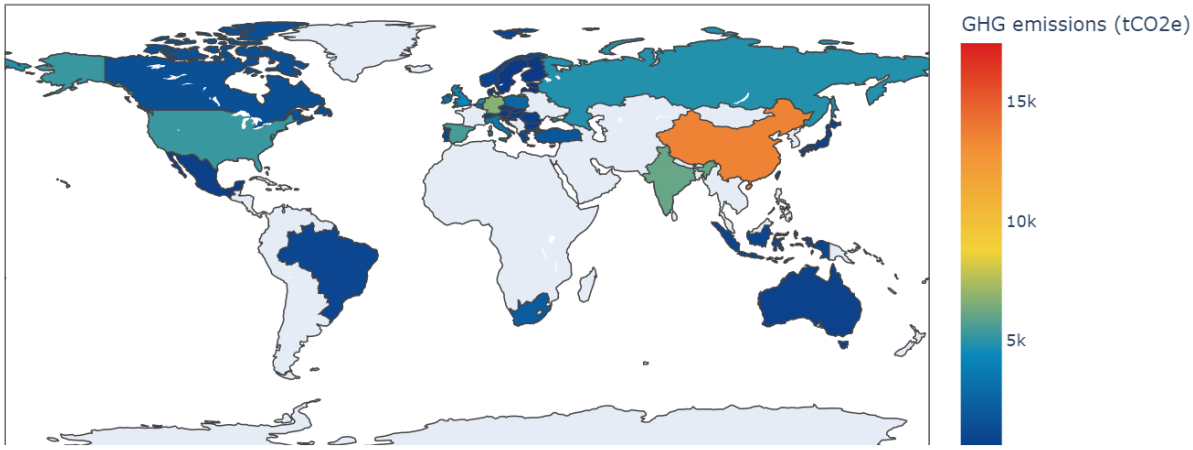


Figure 5.7 | GHG emissions occurring in the ROW (only countries), second round of the first period, total budget, simplified version

The emissions of the second round of the first period vary significantly in total figures for the three scenarios (see Table 5.1). However, the activities that contribute the most for each of them are practically the same as Figure 5.8 shows.

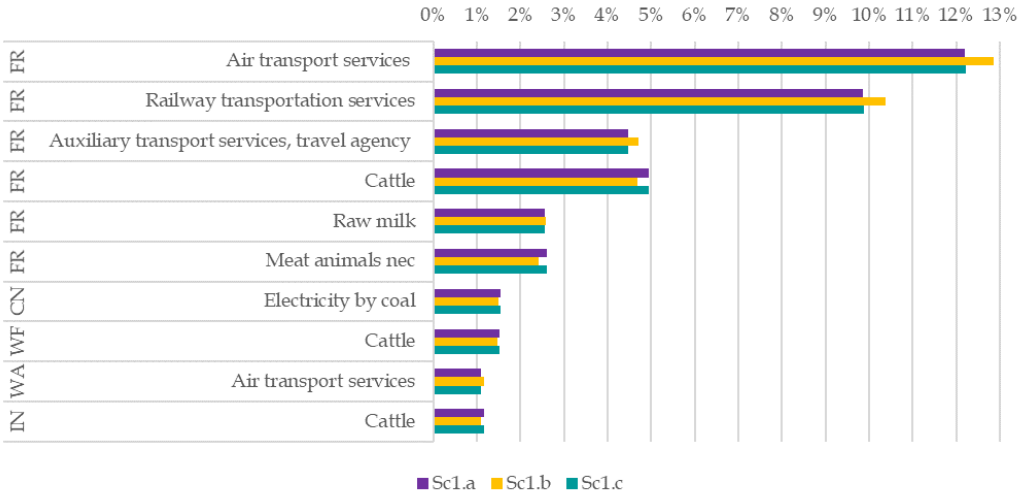


Figure 5.8 | Contribution of activities to the emissions of the second round of the first period, total budget, simplified version

The biggest differences are observed for the scenario Sc1.b, where the high-skilled (HS) households have the higher induced consumption, as presented in Table 5.2. One would expect higher emissions for scenario Sc1.b and lower emissions for scenario Sc1.c, as they present the highest and lowest induced consumption, respectively. However, even though Sc1.c has the lowest expected emissions, scenario Sc1.a has the highest emissions (see Table 5.1).

Table 5.2 | Final consumption expenditure of each income group (low-skilled – LS, medium-skilled – MS, and high-skilled – HS), second round, first period, total budget, simplified version (MEUR)

	LS	MS	HS	Total
Sc1.a	42.98	549.26	353.21	945.45
Sc1.b	37.15	469.03	439.46	945.64
Sc1.c	37.15	469.03	305.78	811.96

The reason for that is the consumption patterns of the low-skilled and medium-skilled households, which are more GHG intensive than high-skilled households' emissions, as observed in Figure 5.9. The figure shows the total GHG emissions occurring as a result of €1 million spent by each income group and highlights the difference in emissions depending on the consumption patterns.

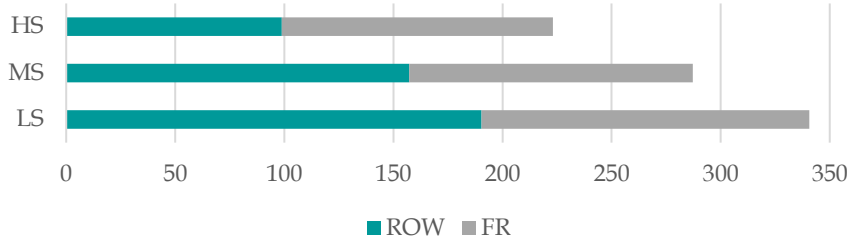


Figure 5.9 | GHG emissions of marginal expenditure (tCO_2e/MEUR)

In the first round of the second period, the GHG emission reductions are 137,247 tons of CO_2e, representing around 10% of the emissions increase observed at the end of the first period (first and second-order effects). Figure 5.10 presents the sources of the emissions reduction. The great majority of the observed reduction corresponds to the avoided direct combustion of fuels in buildings for having improved their energy performance. The other emissions presented in Figure 5.10 occur downstream or upstream regarding the concerned buildings, one part in France and the other part in the ROW.

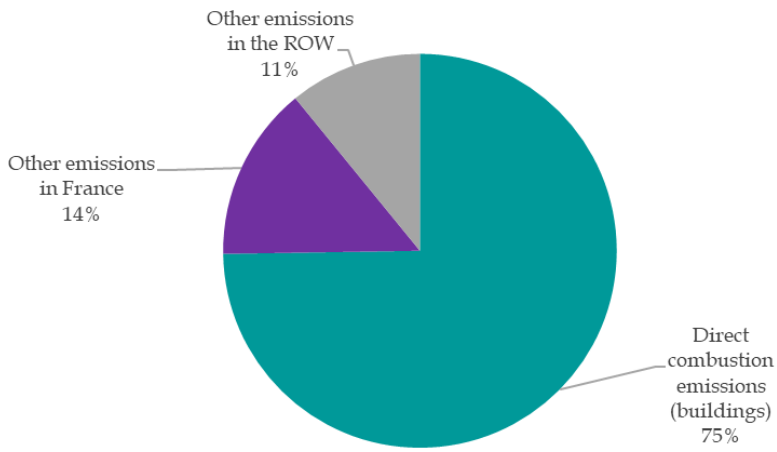


Figure 5.10 | Emissions reduction, second round of the second period, total budget, simplified version

When considering the emission reductions occurring in France, they would be equal to the increase in emissions observed in France for the first round of the first period (413,061 tons of CO_2e) in 3.38 years. When considering the emissions occurring in the ROW, they would be equal in 44 years, and when analyzing the combined emissions, the time needed to compensate the increase in emissions is 7.8 years, which grows to 9.4 years when taking into account the second order effects.

5.1.1.2 Only residential, detailed version

The GHG emissions of the detailed version of the residential buildings are presented round-by-round in Figure 5.11. There is a substantial increase in emissions due to the

perturbation in the first round of the first period (1P1R), followed by a second increase in emissions due to the induced consumption (1P2R). After this, in a second period, there is an essential drop in emissions from the saved energy (2P1R), followed by a slight increase from the induced consumption emissions (2P2R). The reduction in emissions of the second period is more evident in the detailed version since the estimates for the energy savings are higher than in the simplified version of total budget.

Figure 5.11 | Cumulated GHG emissions, round by round, only residential, detailed version ($MtCO_2e$)

The numerical results of the GHG emissions round-by-round are presented in Table 5.3. The second-order effects are not negligible when compared with the first-order effects, representing from 15% (Sc2.c) to 17% (Sc2.a and Sc2.b) of total emissions of the first period.

Table 5.3 | GHG emissions, round-by-round, only residential, detailed version (tCO2e)

	1P1R	1P2R	1P	2P1R	2P2R	2P
Sc2.a	1 583 036	267 514	1 850 550	- 783 135	36 271	- 746 864
Sc2.b	1 583 036	262 926	1 845 962	- 783 135	33 906	- 749 229
Sc2.c	1 583 036	232 892	1 815 927	- 783 135	32 246	- 750 889

The geographic repartition of the emissions differs from the previous results, with a more equilibrated profile between emissions occurring in the ROW and France. However, as shown in Figure 5.12, the countries contributing the most to the increase in emissions are practically the same as the ones observed for the simplified version of the total budget, shown in Figure 5.4. China is the country with the highest contribution as well as in the simplified version of the total budget (representing around 15% of ROW emissions). Germany remains in the second position and increases its contribution from 8% to 9%. Russia is in the third

position, which increases its contribution from 4.9% to 5.2%, in relation to the simplified version of the total budget. The United States increase their contribution (from 3% to 5%) being the country with the fourth highest contribution. Spain decreases its contribution from 5% to 4%, in the fifth position. The other countries do not significantly change their contribution in relation to the simplified version of the total budget, except Turkey, which had appeared in the top 10 countries contributing to the ROW emissions and is now in the 14th position. On the other hand, South Africa did not appear in the top 10 list of the previous version; and, for the current version, it is the tenth country with the highest contribution (increasing the contribution from 1% to 2%.

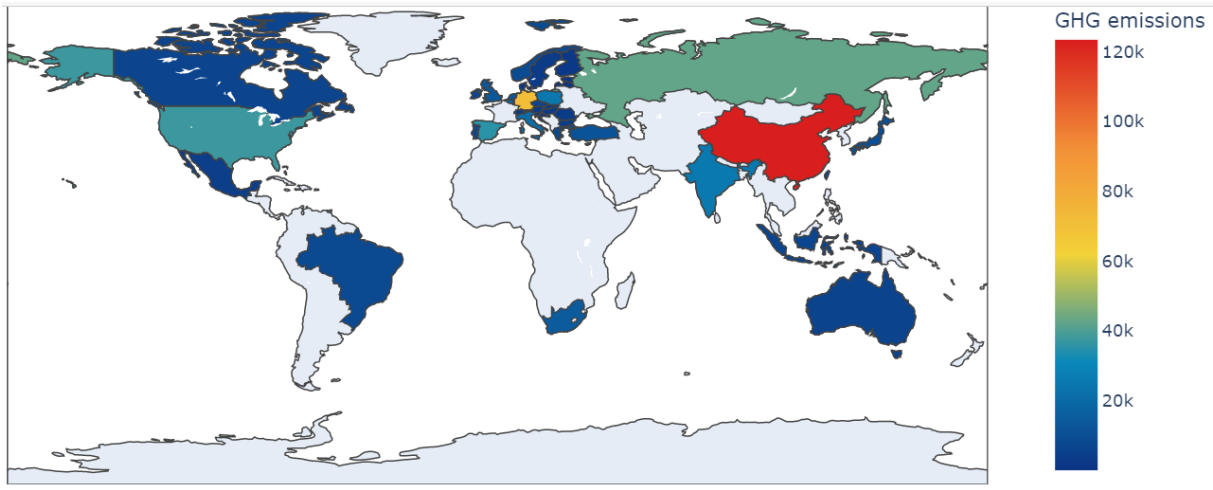


Figure 5.12 | Global emissions in the ROW, first round of the first period, only residential, detailed version (tCO_2e)

The top 10 activities contributing the most to the increase in emissions in France and worldwide are presented in Figure 5.13.

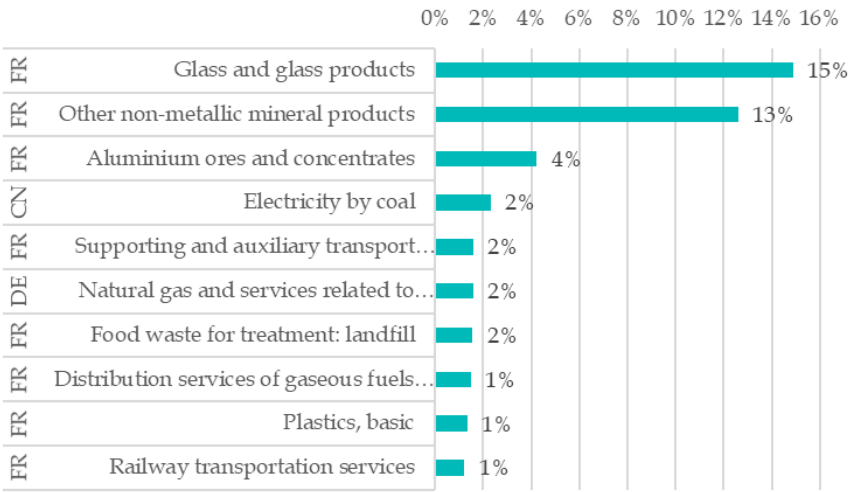


Figure 5.13 | Contribution of activities to total emissions, first round, first period - only residential, detailed version

Glass and glass products appear at the top of the most contributing activities, mainly because of the emissions from producing double-glazed windows. The second activity with higher emissions represents the insulating material (mostly rock wool), then, in the third place, it is the French Aluminium ores and concentrates, which have an increase in total outputs from windows frame. Chinese electricity produced by coal appears in the fourth position. The latter had also appeared in the main contributors for the total budget simplified version, as well as the German natural gas. A possible reason for this is the high emissions of these two activities combined with their significant change in output.

Supporting and auxiliary transport services appear in the fifth position because it is the 10th activity with higher change in total outputs, representing a significant input for the affected activities. With regard to food waste treatment, even if its change in total output is very low (lower than 0.04% of the total change in outputs), the emission coefficient is very high (4,455,977 $MtCO_2e$/MEUR), justifying its high relative importance when compared with other products and services.

In the second period, the emissions reduction from the energy savings is 0.783 $MtCO_2e$, happening in France and the ROW. Figure 5.14 presents the percentages of the emission savings concerning the nature of reductions. Most of them are due to savings in direct combustion of residential buildings (61%) occurring in France, 12% of the reductions also occur in France but are associated with the supply chain of the energy saved.

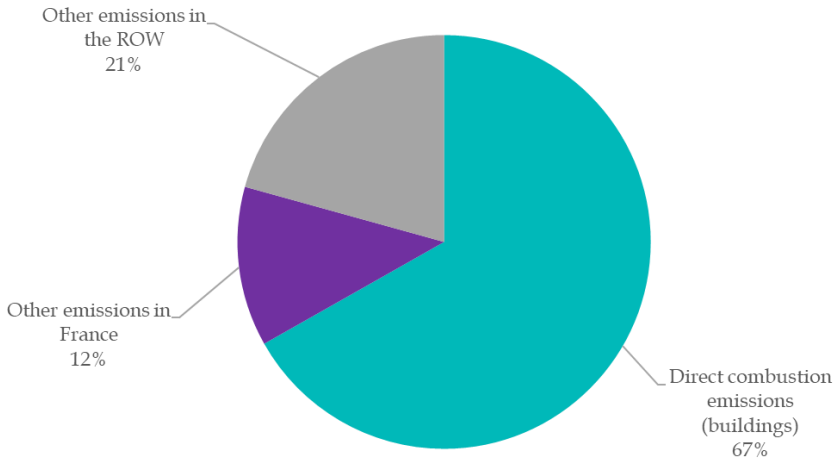


Figure 5.14 | GHG emission savings in the first round of the second period, only residential, detailed version

Differently from the total budget simplified version, the other emissions in the ROW represent more than one-fifth of total reductions, two times more representative than in the previous version. One possible reason for this difference is that the detailed version considers that more than 80% of energy savings come from diesel and natural gas, which present important emissions in the ROW. The products contributing to the decline are crude petrol from Asia and the Pacific, Africa, the Middle East and Russia, and natural gas from Germany.

It is worth mentioning that, even considering that national emissions are less representative in the detailed version of residential buildings, the absolute values of direct energy savings estimated in MENFIS are five times higher than the previous version. The results observed in this version show that the energy savings would compensate for the increase in emissions within 1.23 year in France and 5.07 years in the ROW. When combining the emissions in the ROW and France, the time needed is 2.0 years, growing to 2.4 years, including the induced consumption (1P2R).

5.1.1.3 Only residential, simplified version

The GHG emissions, round-by-round, of the simplified version of the part of the budget dedicated to residential retrofitting are presented in Figure 5.15. The general patterns are the same as the ones observed in the previous versions; however, this version is more similar to the simplified version of the total budget. One of the reasons for that is because both simplified versions have the same assumptions for the exogenous perturbations, respecting the scope of each version (only residential considers only the money spent on thermal retrofitting works conducted on residential buildings and etx.).

There is a substantial increase in the emissions due to the perturbation in the first round of the first period (1P1R), followed by a second increase in emissions due to the induced consumption (1P2R). Then, in a second period, there is an essential drop in emissions due to the saved energy (2P1R), followed by a slight increase from the induced consumption emissions (2P2R). Scenario Sc3.a presents the higher emissions, while scenario Sc3.c has the lowest ones.

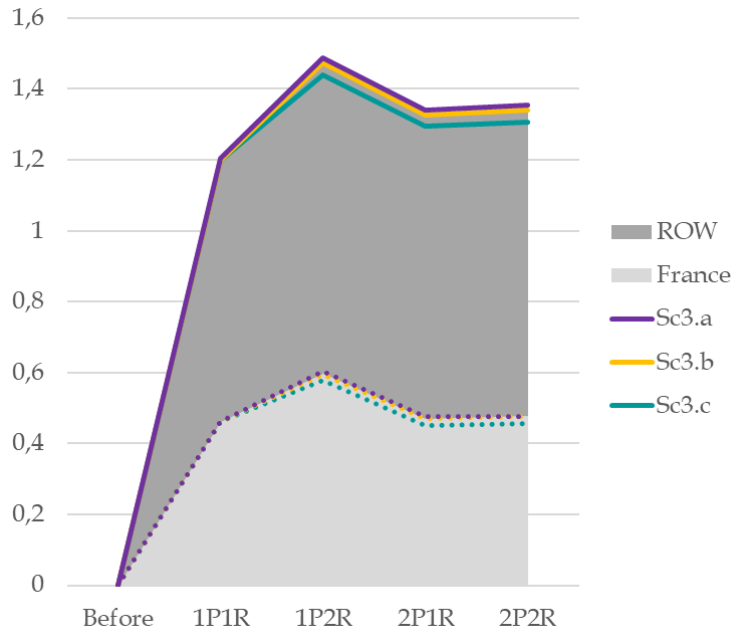


Figure 5.15 | GHG emissions round-by-round, only residential, simplified version ($MtCO_2e$)

The values of the emissions round-by-round are presented in Table 5.4. Compared with the previous results, this version has intermediate GHG emissions in the first round of the first period. The emissions are lower than those of the detailed version because the affected products in the latter are more GHG intensive than construction works. This version presents higher emissions than those of the total budget because, even considering that the scope of the total budget is broader, in this current version, the assumption is that the money from the recovery plan does not cover the whole expenditure. Therefore, total expenditure in this version is higher than in "total budget" version.

Table 5.4 | GHG emissions round-by-round, only residential, simplified version (tCO2e)

	1P1R	1P2R	1P	2P1R	2P2R	2P
Sc3.a	1,198,998	280,272	1,479,270	- 146,083	13,879	- 132,204
Sc3.b	1,198,998	273,818	1,472,816	- 146,083	13,976	- 132,107
Sc3.c	1,198,998	240,539	1,439,537	- 146,083	11,867	- 134,216

In the second round of the first period, the emissions observed in this version are the highest ones when compared with the two previous versions. This happens because the increase in gross domestic product (GDP) is higher in this version, inducing more consumption than in the detailed version (see discussions in Chapter 4). The contribution analysis is the same as the one observed in the version "total budget, simplified", as the foreground is affected by the same activity.

5.1.2 Wastes

5.1.2.1 Total budget, simplified version

An increase in the demand for 5.2 billion euros in construction products and services produce a total 801.1 ktons of wastes in the first round of the first period. Figure 5.16 presents the cumulate wastes produced round-by-round for the three scenarios.

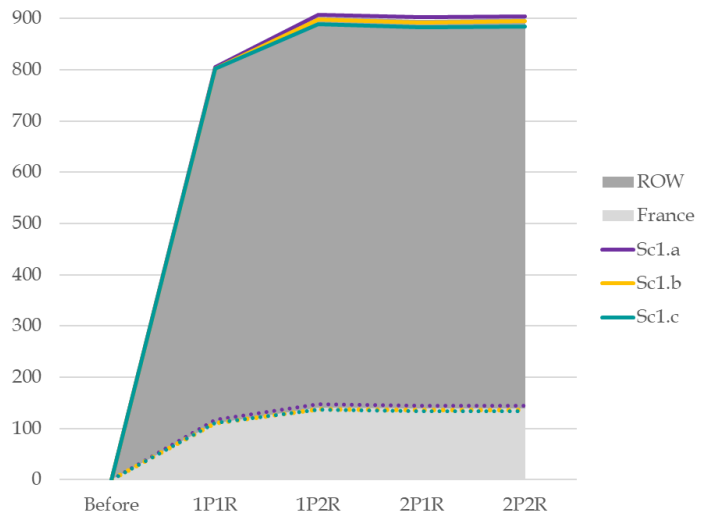


Figure 5.16 | Cumulated wastes generated round-by-round, total budget, simplified version (kton)

As observed in Figure 5.16, the most significant contribution to waste production occurs in the first round of the first period. However, the second round is also substantial compared to the other rounds, which, on the other hand, are negligible, i.e., the reduction in energy consumption does not have any positive effect on the wastes production, according to our results. Besides, there is no significant difference between the scenarios, as observed in the above graph and also in Table 5.5 below.

Nineteen types of wastes are assessed here. The results of wastes produced round-by-round, by type of waste, for the three scenarios can be observed in Table 5.5. The values highlighted in red are the highest ones for each round, representing the waste flow with highest contribution to total waste production.

Table 5.5 | Wastes production, round-by-round, total budget, simplified version (kton)

Type	1P1R	1P2R			2P1R	2P2R		
		Sc1.a	Sc1.b	Sc1.c		Sc1.a	Sc1.b	Sc1.c
Food wastes	4.5	3.3	3.2	2.8	0.0	0.1	0.1	0.0
Manure	38.8	50.8	47.1	43.5	-0.3	1.2	1.3	0.9
Textile wastes	0.9	0.2	0.2	0.1	0.0	0.0	0.0	0.0
Wood wastes	87.2	4.1	3.9	3.6	-0.3	0.1	0.1	0.1
Paper wastes	2.4	0.4	0.4	0.4	0.0	0.0	0.0	0.0
Plastic wastes	6.7	1.2	1.2	1.0	0.0	0.0	0.0	0.0
Glass wastes	1.0	0.3	0.3	0.3	0.0	0.0	0.0	0.0
Ashes	28.9	2.5	2.4	2.1	-0.6	0.1	0.1	0.0
Steel wastes	2.9	0.1	0.1	0.1	0.0	0.0	0.0	0.0
Precious metals wastes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium wastes	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lead wastes	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Copper wastes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
non-ferrous metal wastes	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Construction materials and mining waste (excl. unused mining material)	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oils and hazardous material wastes	12.2	1.1	1.1	1.0	-2.2	0.0	0.0	0.0
Sewage	4.5	2.4	2.4	2.1	0.0	0.0	0.0	0.0
Mining waste	540.1	31.8	30.7	27.3	-1.8	0.7	0.7	0.4
Unused waste	68.4	3.7	3.6	3.1	-0.2	0.1	0.1	0.0
Total	***801.7***	***101.9***	***96.5***	***87.4***	***-5.6***	***2.3***	***2.4***	***1.6***

In the first round of the first period, there is substantial production of mining wastes, wood wastes, manure, ashes, oils and hazardous material wastes, and unused wastes. Mining wastes are the most produced ones, mainly in the ROW, as presented in Figure 5.17.

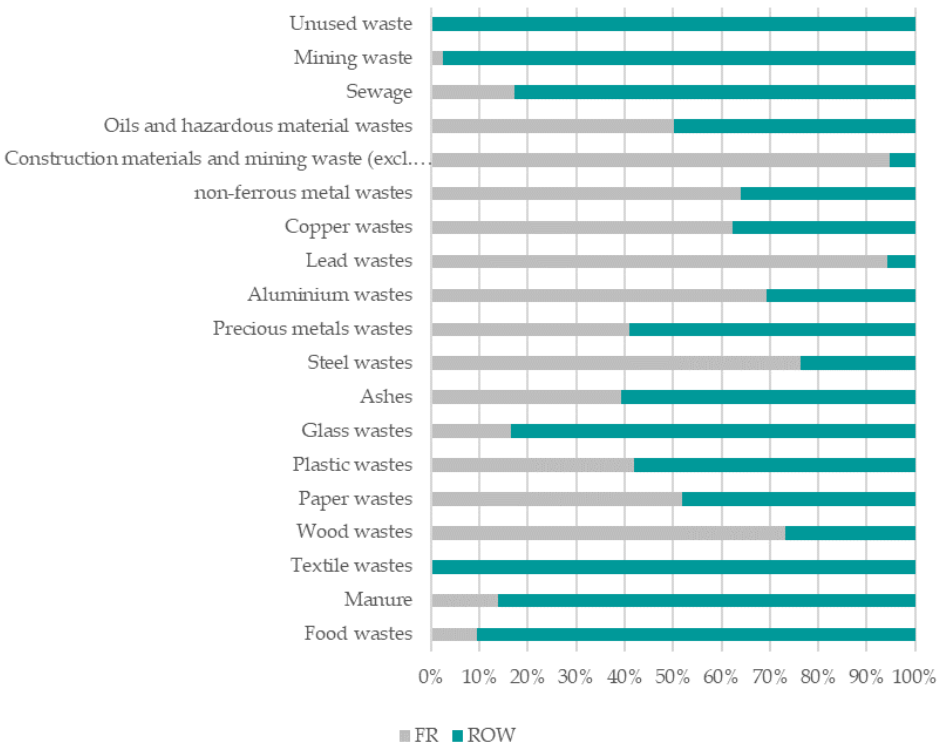


Figure 5.17 | Percentages of geographical production of wastes, by type, the first round of the first period, total budget, simplified version

Mining wastes generated abroad are mainly associated with the production of precious metal ores, occurring in the rest of Asia (WA, 40%), the rest of America (WL, 22%), and the rest of Africa (WF, 3%). The other products contributing to mining wastes are copper ores, iron ores, lead, and zinc, from Australia (AU), France (FR), Poland (PL), Russia (RU), Germany (DE) and rest of America (WL), as presented in Figure 5.18.

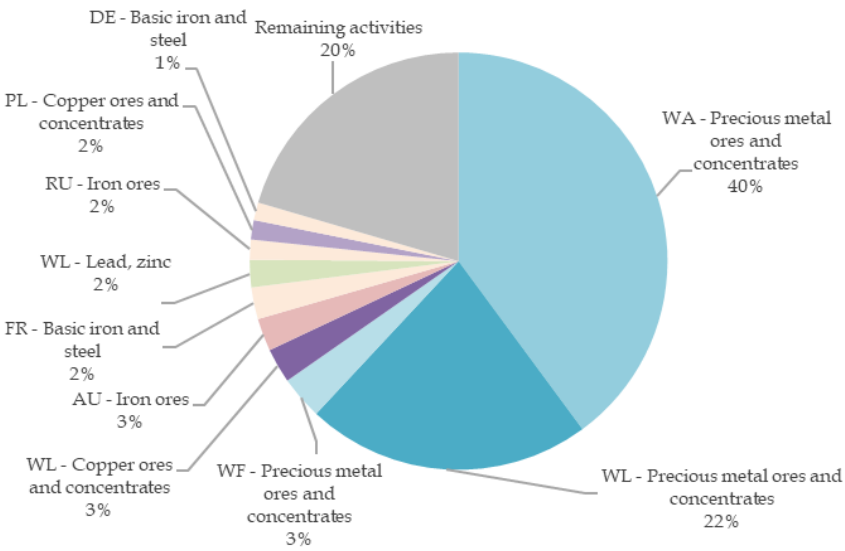


Figure 5.18 | Top 10 contributors to mining wastes production in the first round of the first period, total budget, simplified version

In the second round, **manure** is the most significant contributor to waste production (see Table 5.5). The repartition between wastes produced in France and in the ROW is even more pronounced in this second round for most of the categories, with the exception of manure and sewage, as shown in Figure 5.19.

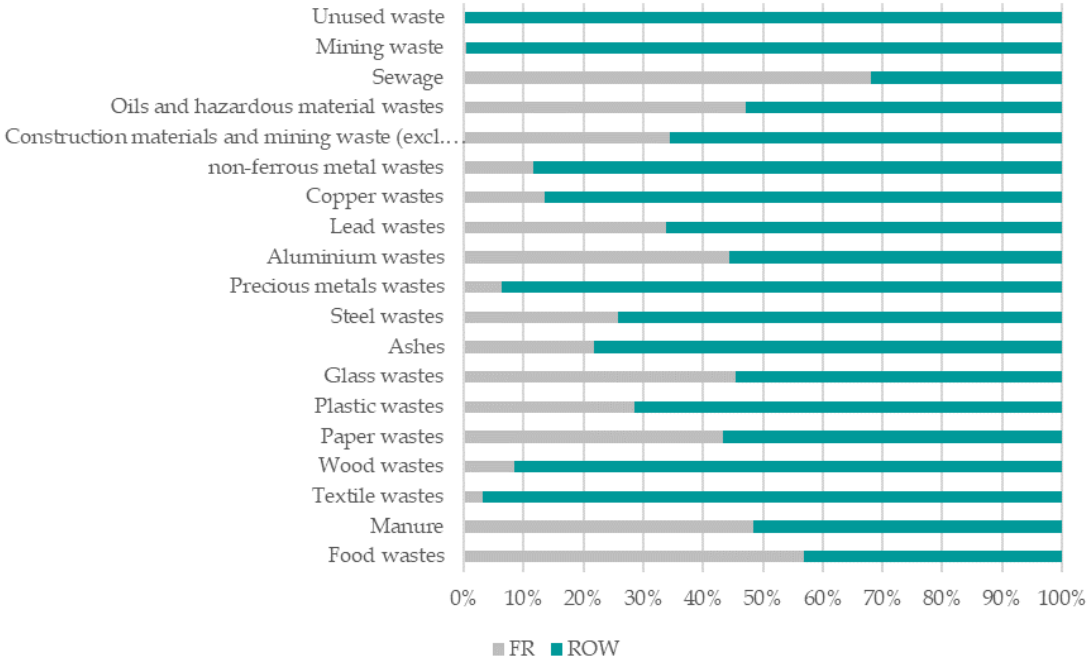


Figure 5.19 | Percentages of geographical production of wastes, by type, the second round of the first period, total budget, simplified version

The weighty production of manure observed in the second round of the first period is a result of the induced consumption and is mainly explained by the increase in the household's direct consumption of meat and milk, as presented in Figure 5.20.

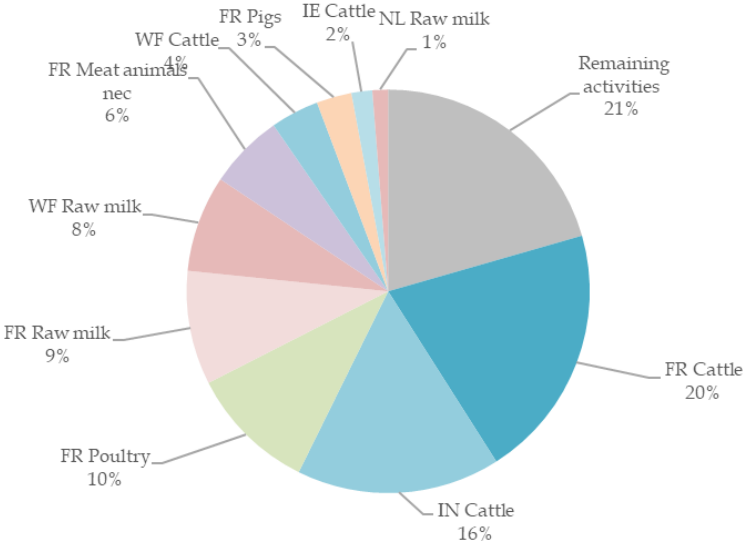


Figure 5.20 | Top 10 contributors to manure production in the second round of the first period, Sc2.a, total budget, simplified version

Cattle products (in blue) appear four times in the top ten contributors in France (FR), India (IN), Africa (WF) and Ireland (IE). This means that an increase in demand for food products in France will induce an increase in cattle production in India, Africa, Ireland and France, which will generate around 34 ktons of manure. The same happens for raw milk, as the increase in demand for milk in France will trigger an increase in production of milk in Africa (WF) and the Netherlands (NL), which contributes to generating 7 ktons of manure.

The energy savings reduce the waste production by 5.6 ktons, mainly the waste category "oils and hazardous material wastes", which can be justified by the reduction in electricity produced by nuclear. If this annual drop is kept the same year by year, it would compensate for the initial increase in waste production in 144 years. When only considering the waste produced in France and the reductions occurring in France, the time needed to compensate for the increase in production drops to 41 years, resulting from the massive ROW contribution to total waste production.

5.1.2.2 Only residential, detailed version

As mentioned in Section 4.4.2, MENFIS simulates the number of retrofitting works by type of equipment on a yearly basis. The information is presented in numerous levels of detail. One of them is the number of retrofitting works according to the initial energy source in the building. For example, the number of new gas-fueled boilers installed in 2020 in houses initially using natural diesel as the primary energy source. Therefore, it is possible to know how many replacements were made as a consequence of the increase in financial aid from the Recovery Plan.

The results obtained are presented in Table 5.6. The only equipment that replaced an initial boiler was a heat pump air/water, in both apartments and houses. The number of replaced equipment units is thus associated with direct wastes, by following the end-of-life profile of the products as described in their EPD.

Table 5.6 | Number of replacements due to the Recovery Plan

		Initial equipment:	
	Replaced by:	Gas condensing boiler	Fuel condensing boiler
Individual dwelling	Heat pump - air/water	8471	698
Collective dwelling	Heat pump - air/water	5180	444

As explained in Section 1.1.1, a French EPD database (INIES) makes available the "environmental data" of construction products and equipment used in the construction systems in France. Environmental data comprises the existing EPDs of construction products (FDES) and equipment (PEP) that are commercialized in France (declared by producers, a consortium of producers. etc.), as well as the default environmental data (DED) and environmental data of services made available by the State. Default environmental data are

data used in the absence of an environmental statement of the construction or decoration product or the equipment chosen to improve the completeness of buildings' life cycle assessment. For the four types of equipment considered to be replaced, as presented in Table 5.6, we used the composition provided by the two collective declarations (gas condensing boiler, individual and collective dwellings)[21] and two DEDs (fuel condensing boiler, individual and collective dwellings)[22]. Their compositions are presented in Table 5.7.

Table 5.7 | Composition of fuel and gas boilers

	Fuel condensing boiler		Gas condensing boiler	
	Individual dwelling	Collective dwelling	Individual dwelling	Collective dwelling
Plastic	2%	1%	13%	5%
Steel	85%	89%	59%	75%
Aluminium	6%	3%	15%	12%
Copper	8%	7%	11%	7%
Non-ferrous metal	0%	0%	2%	0%
Total mass (kg)	*363*	*593*	*40*	*187*

Besides, all installed windows are considered to be a replacement for old simple glazed windows. The composition of a window is based on the average of the three types of frame, namely aluminium, PVC and wood, based on their market shares. Their components and respective masses are taken from the windows' EPDs, and the mass of the glass was divided by two (approximate approach as the simple glazed windows are considered to have half of the amount of glass in relation to double-glazed windows). The values considered in this thesis are presented in Table 5.8.

Table 5.8 | Composition of windows (kg/m²)

Component	Windows. aluminium-framed	Windows. PVC-framed	Windows. wood-framed
Aluminium	5.5	-	-
Iron (steel. cast iron. etc)	-	1.3	1.5
PE-HD	-	-	0.4
PVC	-	11.5	0.0
Epoxy	-	-	1.1
Plastics	1.9	-	-
Glass	8.8	8.2	6.7
Wood	-	-	17.5
Total	16.2	21.0	27.3

[21] For gas condensing boiler: two PEPs declared by UNICLIMA "Chaudière à condensation gaz individuelle mixte" and "Chaudière à condensation gaz collective chauffage seul (v.1.2)"

[22] For fuel condensing boilers : two DEDs "Chaudière fioul [P=100kW] - DONNEE ENVIRONNEMENTALE PAR DEFAUT (v.1.1)" and "Chaudière fioul [P=25kW] - DONNEE ENVIRONNEMENTALE PAR DEFAUT (v.1.1)"

For obtaining the direct wastes produced by the replacement, these proportions were applied to the total mass to get the likely waste flow. The total amount of produced waste is 2,485 tons, with the composition as shown in Figure 5.21.

Figure 5.21 | Direct wastes profile (ton)

The wastes produced by the economic activities that are affected by the perturbation are presented in Figure 5.22.

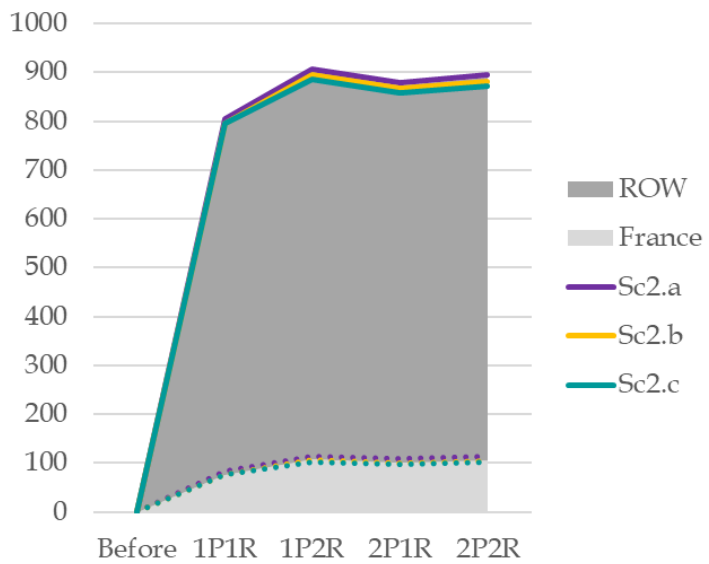


Figure 5.22 | Wastes produced round-by-round, only residential, detailed version (kton)

The total waste produced in the two periods varies from 872 ktons (Sc2.c) to 887 ktons (Sc2.a). Most wastes are produced in the first round of the first period (1P1R), mainly in the

ROW. The part produced in France is 76.2 ktons, 2.5 ktons from direct replacements (or 3% of total French waste production).

The wastes produced round-by-round, per type of waste, for the three scenarios are presented in Table 5.9. As well as for the detailed version of the total budget, the higher values for each round are highlighted in red.

Table 5.9| Wastes production, round-by-round, only residential, detailed version (kton)

Type	1P1R	1P2R			2P1R	2P2R		
		Sc1.a	Sc1.b	Sc1.c		Sc1.a	Sc1.b	Sc1.c
Food wastes	8.1	3.5	3.5	3.1	-0.3	0.5	0.4	0.4
Manure	57.7	50.3	47.4	43.8	-2.6	8.6	8.2	7.9
Textile wastes	1.1	0.2	0.2	0.1	0.0	0.0	0.0	0.0
Wood wastes	36.4	4.2	4.1	3.7	-0.4	0.6	0.6	0.6
Paper wastes	3.7	0.5	0.4	0.4	0.0	0.1	0.1	0.1
Plastic wastes	13.1	1.2	1.2	1.1	-0.3	0.2	0.2	0.2
Glass wastes	1.7	0.3	0.3	0.3	0.0	0.0	0.0	0.0
Ashes	43.1	2.6	2.5	2.3	-2.6	0.4	0.3	0.3
Steel wastes	2.7	0.1	0.1	0.1	0.0	0.0	0.0	0.0
Precious metals wastes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium wastes	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lead wastes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Copper wastes	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
non-ferrous metal wastes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Construction materials and mining waste (excl. unused mining material)	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oils and hazardous material wastes	18.8	1.2	1.2	1.0	-6.9	0.2	0.2	0.1
Sewage	7.6	2.6	2.6	2.3	-0.3	0.3	0.3	0.3
Mining waste	523.8	33.2	32.4	28.9	-13.6	4.6	4.3	4.1
Unused waste	79.7	3.9	3.8	3.4	-1.6	0.5	0.5	0.5
Total	798.3	103.9	99.6	90.4	-28.7	16.1	15.2	14.5

The geographical production of wastes varies depending on the waste typology. Figure 5.23 presents the repartition of the wastes generated in France and in the ROW, for the nineteen types included in this assessment. The results show that the location of the waste production varies considerably depending on the typology of waste. For example, construction materials are primarily produced in France, because of the high weight of demolition wastes in comparison with the wastes associated with those generated during raw material production processes. On the other hand, textile wastes are mainly produced in other countries as textile production is concentrated in Asia and the Pacific.

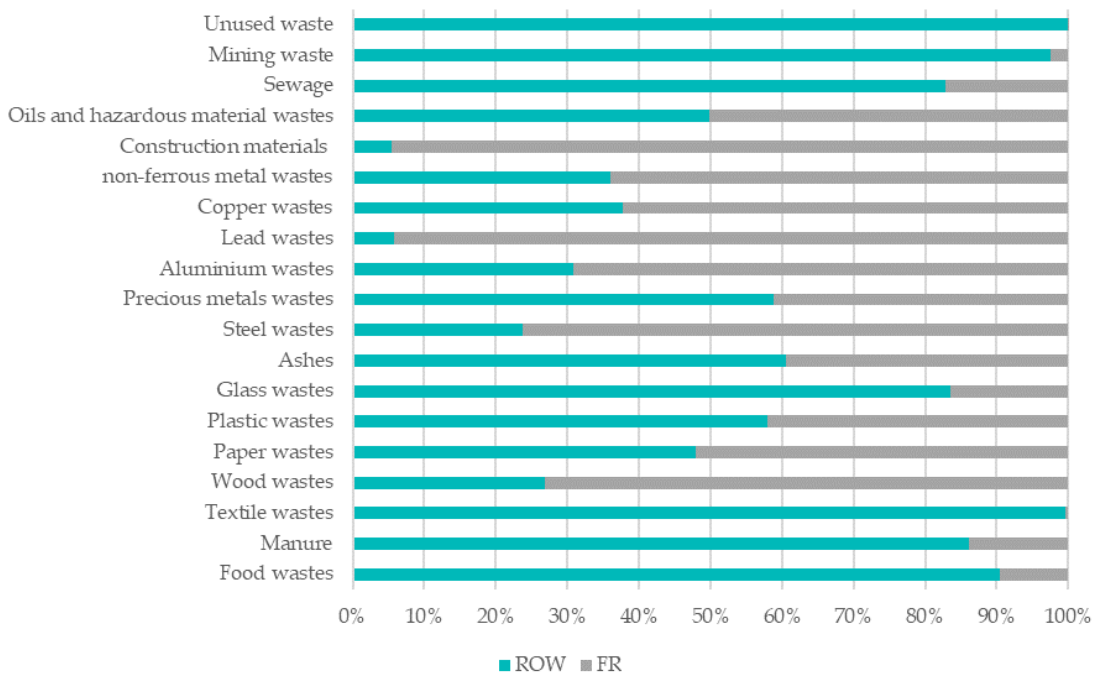


Figure 5.23 | Geographical distribution of the wastes produced in the first round of the first period, only residential, detailed version

Another example of waste mainly produced in the ROW is mining waste. This category represents around two-thirds of total wastes produced in the first round of the first period. The most affected countries and regions are Asia (WA), Africa (WF), the Americas (WL), Australia (AU), Russia (RU), Poland (PL) and Germany (DE), as presented in Figure 5.24.

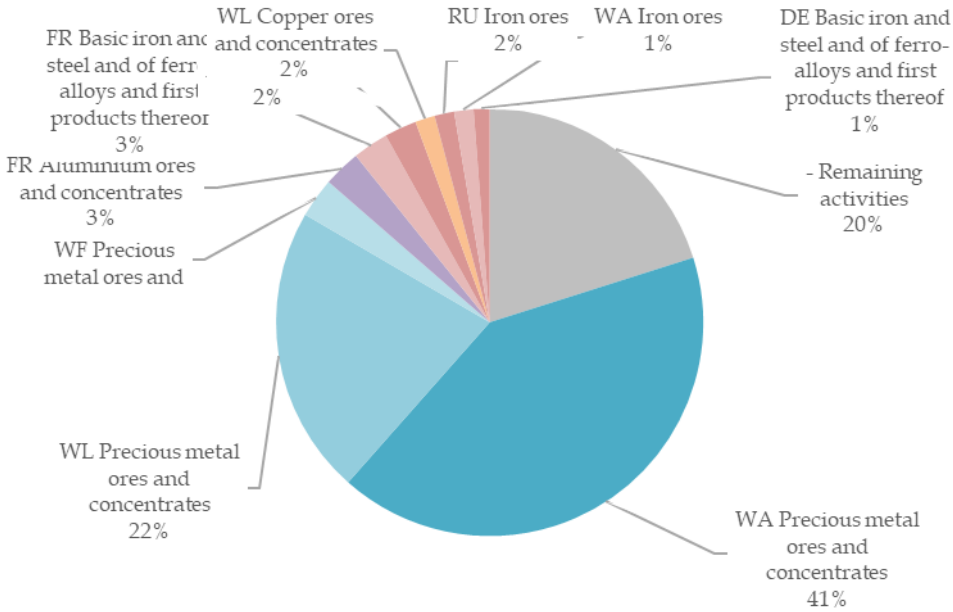


Figure 5.24 | Economic activities producing the mining wastes in the first round of the first period, only residential, detailed version (kton)

Precious metal ores and concentrates (in blue) are the top 3 products contributing to the production of wastes occurring due to the increase in demand for heating equipment, insulation materials and windows. This corresponds to these products presenting a higher intensity of mining wastes produced by MEUR, as illustrated in Figure 5.25.

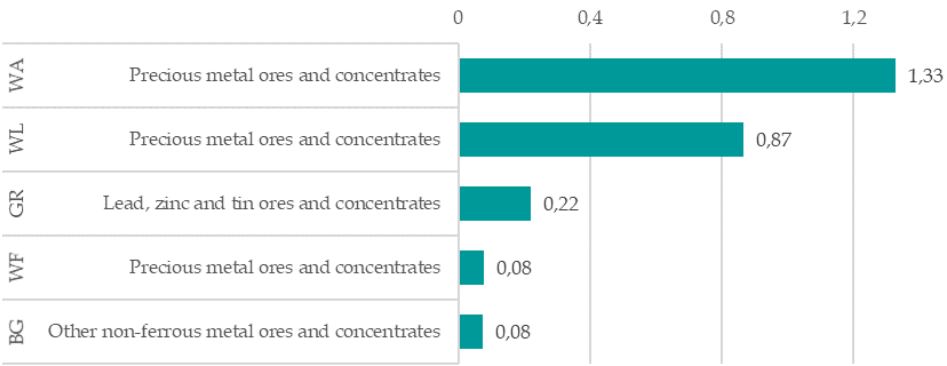


Figure 5.25 | Activities presenting the five higher intensities of mining waste production (ton of mining wastes/MEUR)

In the second round of the first period, as well as what was observed in the simplified version of the total budget, manure is the most produced waste type, with major contributors being the same as discussed before. Figure 5.26 presents the contribution analysis for the scenario Sc2.a, however, the results for the other two scenarios are the same.

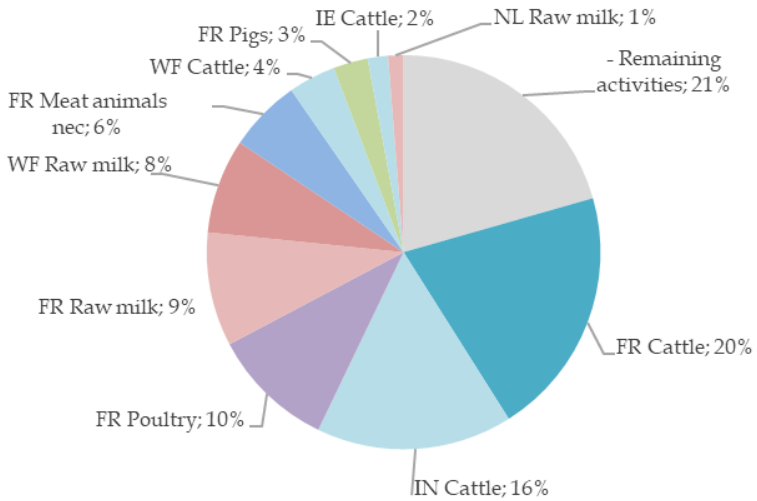


Figure 5.26 | Top 10 contributors to manure production in the second round of the first period, Sc2.a, only residential, detailed version

5.1.2.3 Only residential, simplified version

Figure 5.27 presents the cumulate wastes produced round-by-round for the three scenarios of the "only residential, simplified" version. Compared with the previous results, this current version presents the highest waste production in the first period and intermediate values of production in the second period.

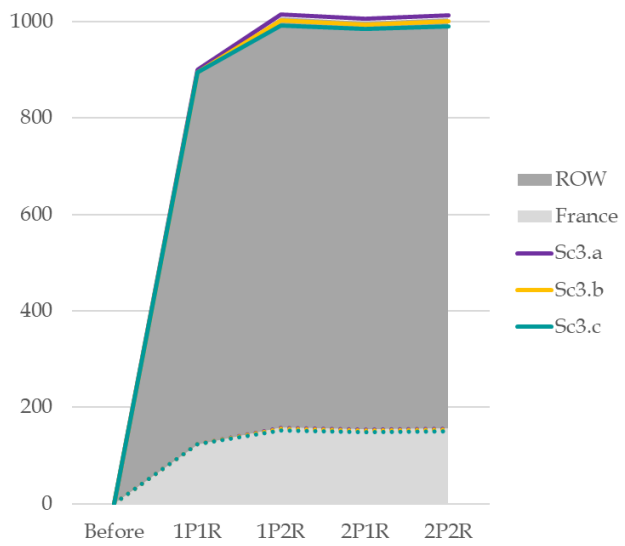


Figure 5.27 | Wastes produced round-by-round, only residential, simplified version (kton)

The values of the waste production round-by-round are presented in Table 5.10. As well as in the previous versions, the highest value of each round is highlighted in red.

Table 5.10 | Waste production, round-by-round, only residential, simplified version (kton)

Type	1P1R	1P2R			2P1R	2P2R		
		Sc3.a	Sc3.b	Sc3.c		Sc3.a	Sc3.b	Sc3.c
Food wastes	5.0	3.7	3.6	3.1	-0.1	0.2	0.2	0.2
Manure	43.3	56.6	52.6	48.5	-0.5	3.3	3.4	3.0
Textile wastes	1.1	0.2	0.2	0.2	0.0	0.0	0.0	0.0
Wood wastes	97.3	4.6	4.4	4.0	-0.5	0.2	0.2	0.2
Paper wastes	2.7	0.5	0.5	0.4	0.0	0.0	0.0	0.0
Plastic wastes	7.4	1.4	1.3	1.2	-0.1	0.1	0.1	0.1
Glass wastes	1.2	0.3	0.3	0.3	0.0	0.0	0.0	0.0
Ashes	32.3	2.8	2.7	2.4	-0.8	0.1	0.1	0.1
Steel wastes	3.3	0.1	0.1	0.1	0.0	0.0	0.0	0.0
Precious metals wastes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aluminium wastes	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lead wastes	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Copper wastes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-ferrous metal wastes	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Construction materials and mining waste (excl. unused mining material)	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oils and hazardous material wastes	13.6	1.3	1.2	1.1	-2.9	0.1	0.1	0.1
Sewage	5.0	2.7	2.7	2.3	-0.1	0.1	0.1	0.1
Mining waste	602.6	35.5	34.2	30.5	-2.6	1.8	1.8	1.5
Unused waste	76.3	4.1	4.0	3.5	-0.3	0.2	0.2	0.2
Total	*894.6*	*113.7*	*107.7*	*97.5*	*-7.9*	*6.2*	*6.3*	*5.4*

The proportions of the results are the same as those observed in the "total budget, simplified version"; however, the magnitude of each produced waste is higher here proportionally to the increase in perturbation (1.12 times bigger).

This means that for each round, the results are higher than those of the total budget. In the second period, the waste production in this version is also higher than the one observed in the detailed version of residential buildings. This is because the multiplier effect of this version is higher, as discussed before. For the second period, however, the magnitude of waste production/reduction of detailed version is higher than in this version. This is because the detailed version has a higher magnitude of exogenous perturbation for energy savings.

5.1.3 Energy consumption

5.1.3.1 Total budget, simplified version

The energy consumption (use) cumulated through the periods (and rounds) follows the same patterns as the previous two categories. The energy use presented in Figure 5.28 considers the fossil and nuclear energy use, as explained in Section 3.4, and also the direct energy consumed by residential and public buildings for heating.

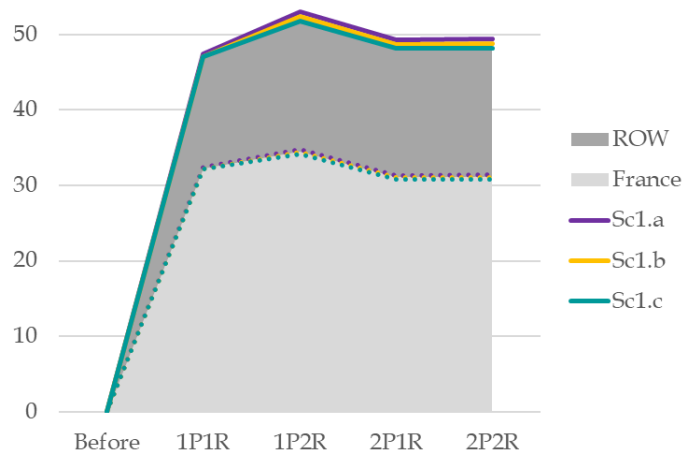


Figure 5.28 | Cumulative energy use (PJ), total budget, simplified version

The values of the round-by-round energy use are presented in Table 5.11.

Table 5.11 | Energy use, round-by-round, only residential, total budget, simplified version (PJ)

Scenario	1P1R	1P2R	2P1R	2P2R
Sc1.a	47.0	5.6	-3.7	0.1
Sc1.b	47.0	5.3	-3.7	0.1
Sc1.c	47.0	4.8	-3.7	0.1

The substantial increase in energy use in the first round of the first period results from the demand for construction products, which are energy-intensive products, and from the changes occurring in their supply chain. The part of the energy use occurring in the ROW is presented in Figure 5.29.

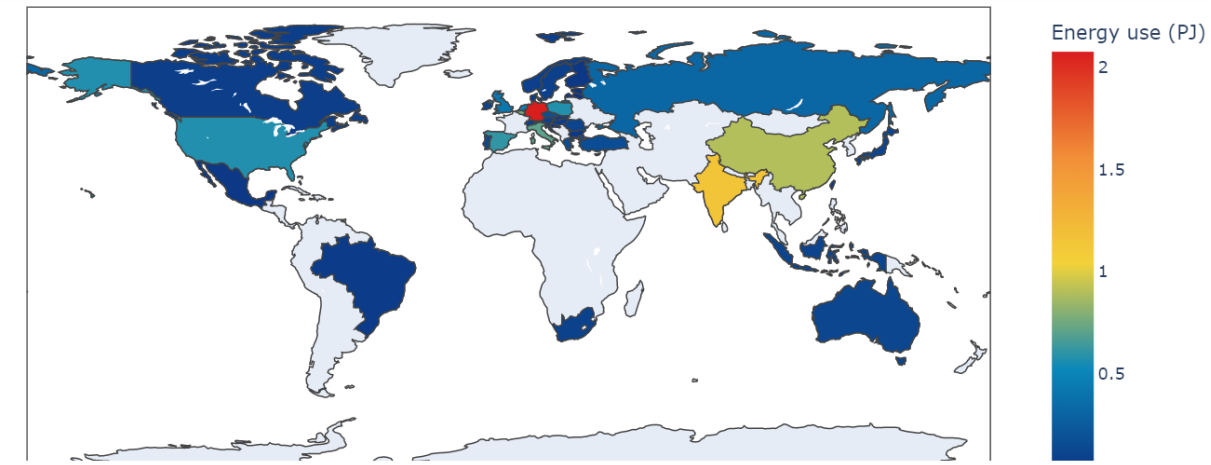


Figure 5.29 | Energy use in the ROW countries, first round of the first period, total budget, simplified version (PJ)

The countries with the highest energy consumption are Germany (DE) (14% of ROW energy use), India (IN) (8%), China (CN) (6%), Italy (IT) (5%), Spain (ES) (4%), Poland (PL) (4%), and the United States (US) (4%). Figure 5.30 shows the top 10 contributors to the increase in energy use observed in the first round of the first period.

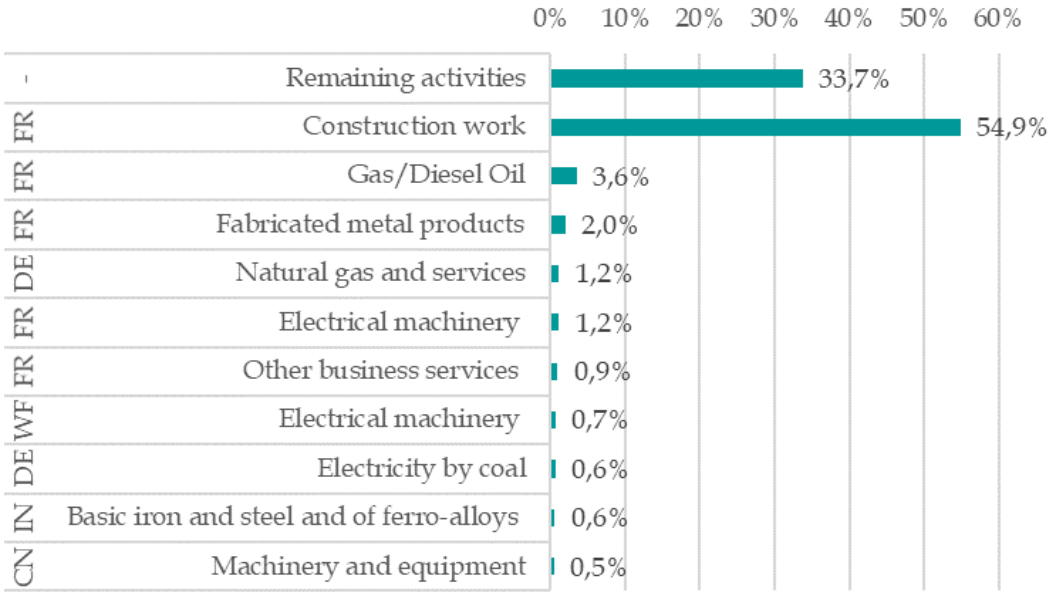


Figure 5.30 | Contribution of products to the total energy use of the initial perturbation, total budget, simplified version

The construction work activity itself contributes to more than half of the increase in total energy use due to the perturbation. The construction works aggregate the construction products and services, which are auto-consumed inside the category, i.e., part of the construction outputs (23%) remain as inputs for construction works. This justifies the high contribution of the construction works to total energy consumption.

The second highest contributor is gas and diesel, followed by metal products in France. Gas and diesel oil products represent less than 0.3% of the total inputs of construction works; however, since they are one of the most energy-intensive products (92 TJ/MEUR), their use in the supply chain activities affected by the perturbation justifies the high contribution observed in Figure 5.30. On the other hand, metal products represent around 10% of total inputs of construction work, and they present 9.2 TJ deprived energy/MEUR output, so the combination of a non-negligible embodied energy and high contribution to total inputs justify their high contribution in Figure 5.30. The fourth contributor is the gas and diesel from Germany, for the same reason as for the high contribution of French gas and diesel.

The German natural gas and services represent less than 0.2% of the total inputs of the construction works, however, its change in total outputs represents around 1% of total change in outputs after the perturbation (multiplier effect). Since this product has an embodied energy of 199.7 TJ/MEUR, and for the same reason as aforementioned for French gas and diesel oil, it appears in the top 5 list of contributors.

Electrical machinery is also a significant contributor to the total energy use of construction products, and they represent 4% of total construction work inputs and relatively low energy use (4.9 TJ/MEUR).

In the second round of the first period, a second increase in energy consumption is observed, as presented in Figure 5.28. The difference in the results for the three scenarios is not significant, as they present the same top 10 contributors, as shown in Figure 5.31.

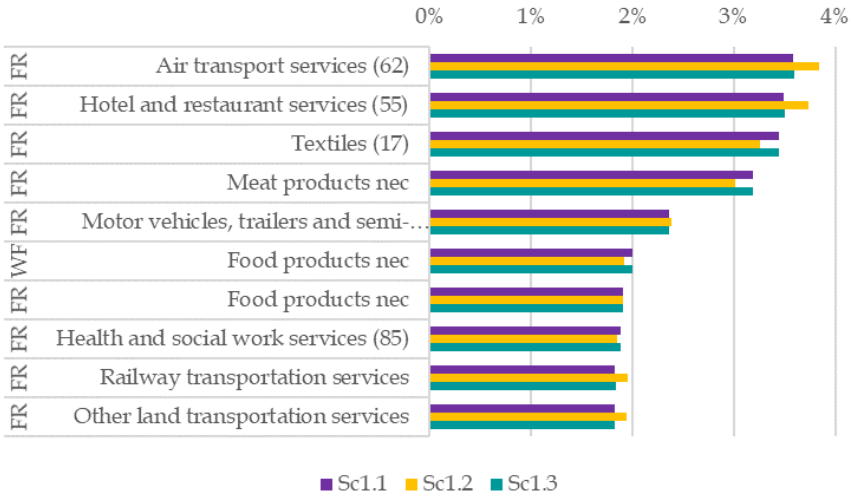


Figure 5.31 | Contribution of products to total energy use in the second round of the first period, total budget, simplified version

All of these activities are directly affected by induced consumption. The two most important contributors are the air transport services and hotel and restaurant services, which are included in the marginal expenditure on leisure activities and railway and other land transportation services.

Textiles are included in the marginal expenditure for clothing and present relatively high embodied energy (17 MJ/MEUR). Meat and food products (French and African) are included in the marginal expenditure on food and present relatively low embodied energy (7.2 MJ/MEUR for food and 4.7MJ/MEUR for meat). Motor vehicles are part of the marginal expenditure on new vehicles, presenting embodied energy of 10.9 MJ/MEUR. Finally, health and social work services are included in the marginal expenditure on healthcare and show a low embodied energy value 1.9MJ/MEUR.

The drop in energy use observed in the first round of the second period is a combination of the reduction in direct energy consumed in the buildings (residential and public administration buildings) and the decrease in energy consumption as a result of the changes in the supply chain activities in France and in the ROW, as presented in Figure 5.32.

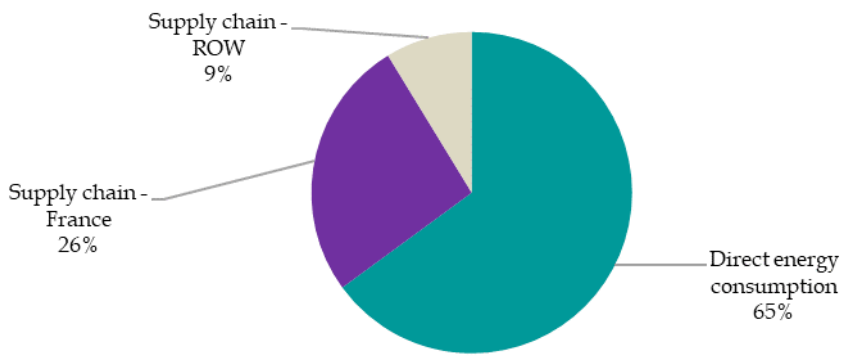


Figure 5.32 | Sources of the decrease in energy use in the first round of the second period, total budget, simplified version

The great majority of the reduction is due to the direct energy drop in consumption, followed by the decrease in the French supply chain embodied energy use, representing more than one-fourth of the reductions. The total amount of energy saved is 3.7 PJ, around 8% of the energy consumption increase due to the initial perturbation, meaning that the avoided energy will equal the gain from the perturbation in 12.7 years.

The second distribution round is less representative when compared to the previous ones. For scenario Sc1.a, the second round represents 4.5% of the decrease observed in the first round. For scenario Sc1.b it is 4.6%and for scenario Sc1.c it is 1.6%. This means that the energy saved in the first round of the second period outweighs the rebound effects of re-spending the saved money. When considering these rebound effects, the avoided energy use will be equal

to the energy use increase observed in the perturbation (first round of the first period) in 13.1 years.

5.1.3.2 Only residential, detailed version

The results for the energy consumption (fossil and nuclear energy use) are presented in Figure 5.33. When compared to the results observed for the simplified version of the total budget, the decrease in the first round of the second period is more evident, the difference is mainly associated with higher absolute energy savings estimated by MENFIS.

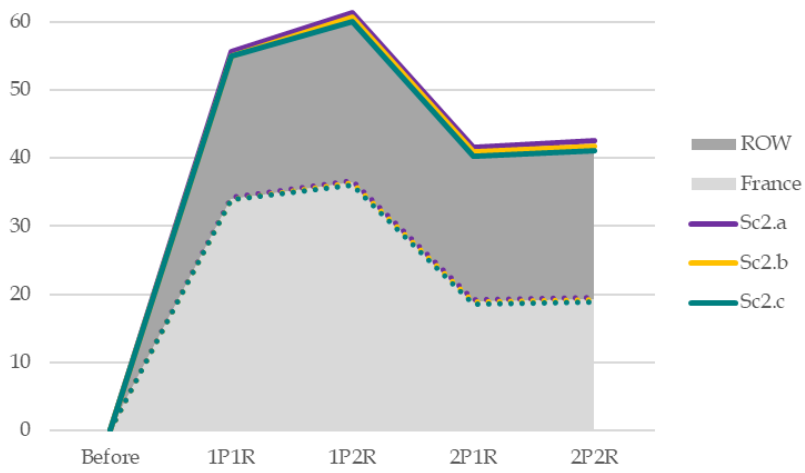


Figure 5.33 | Cumulative energy use (PJ), only residential, detailed version

The increase observed in the first round of the first period is 55.1 PJ, 34 PJ in France and 21.1 in the ROW. When considering the energy use in France, it represents approximately 3.4% of the total energy used in residences for heating in France, in 2020. The decrease observed in the second period of 17.5 PJ, about one-third of the increase observed in the first round of the first period, or 29% of the total increase in energy use (first and second-order effects).

The values of the energy use round-by-round are presented in Table 5.12.

Table 5.12 | Energy use, round-by-round, only residential, detailed version (PJ)

Scenario	1P1R	1P2R	2P1R	2P2R
Sc2.a	55.1	5.8	-19.7	0.8
Sc2.b	55.1	5.6	-19.7	0.8
Sc2.c	55.1	5.0	-19.7	0.7

As observed in Figure 5.33, the increase in energy use observed in the first round of the first period occurs mainly in France. The products representing the highest five contributions to this increase in energy use are shown in Figure 5.34.

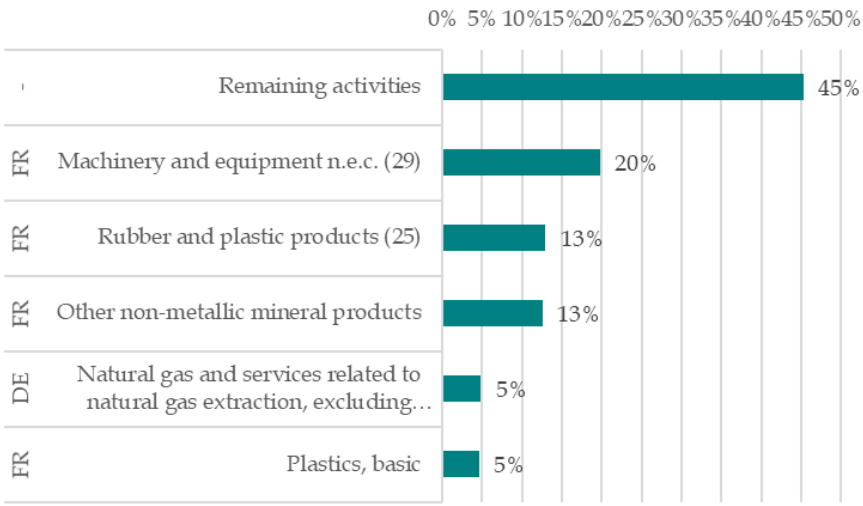


Figure 5.34 | Contribution of products to total energy use of the initial perturbation, only residential, detailed version

Three out of the five products appearing in Figure 5.34 compose the perturbation, meaning that their production is one of the reasons for a high contribution to energy use. The first one is 'machinery and equipment, the cause of 20% of total energy use. These products refer to boilers, heat pumps, and fireplace units defined in the perturbation.

'Rubber and plastic products' represent the PVC in the frames of windows, the expanded polystyrene (EPS) extruded polystyrene (XPS) and polyurethane (PUR), the three used for walls and roofs/attics insulation. Their production contributes to 13% of total energy use.

The third highest contributor is 'Other non-metallic products' representing the rock wool for wall and roof/attic insulation, and its production contributes to around 13% of total energy use. 'Natural gas and resources' from Germany appear in the fourth position. The possible reason for this high contribution from German natural gas is that German products appear in the most significant inputs for the products affected by the change in demand. For example, German rubber and plastic products represent the 12th highest input for the French rubber and plastic products. The German machinery and equipment are the 13th higher input for the French machinery and equipment, the same for aluminium products.

Finally, 'plastics, basic' appear as the fifth contributor to energy use in the first round of the first period. This happens mainly because French 'plastics, basic' supply 18% of the 'rubber and plastic products' total inputs. Therefore, the production of these raw materials used to produce the PVC, EPS, SPX and PUR represents 5% of total energy use.

As presented in Table 5.12, the increase in energy use varies from 5.0 PJ (Sc2.c) to 5.8 PJ (Sc2.a), in the second round of the first period. This increase represents around 16% of the growth observed in the first round for the three scenarios. Figure 5.35 presents the products that contribute to this increase in energy use for the three scenarios.

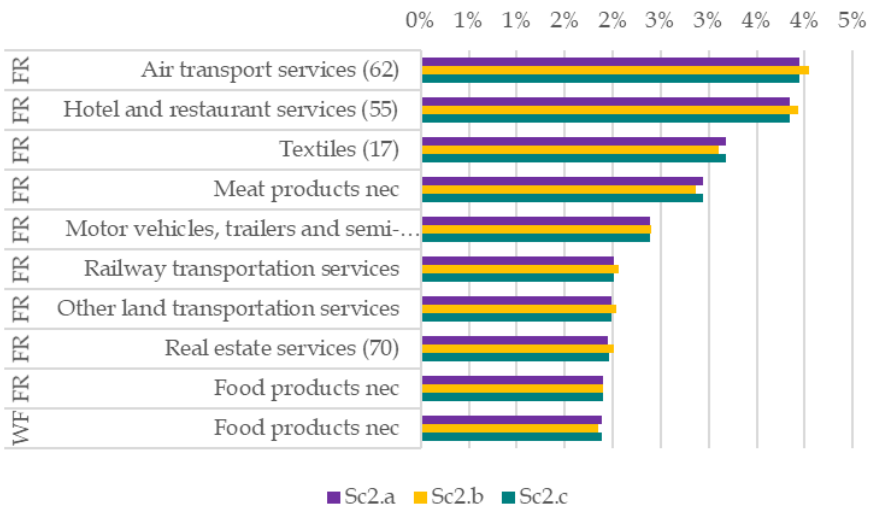


Figure 5.35 | Top 10 contributors to the energy use of the induced consumption, only residential, detailed version

Air transport services are at the top of the products and services contributing to the energy use observed in the induced consumption. This is because it is one of the most energy-intensive activities of the energy savings occurring primarily in France, as one would expect. The energy use in France represents 88% of total savings, as presented in Figure 5.36.

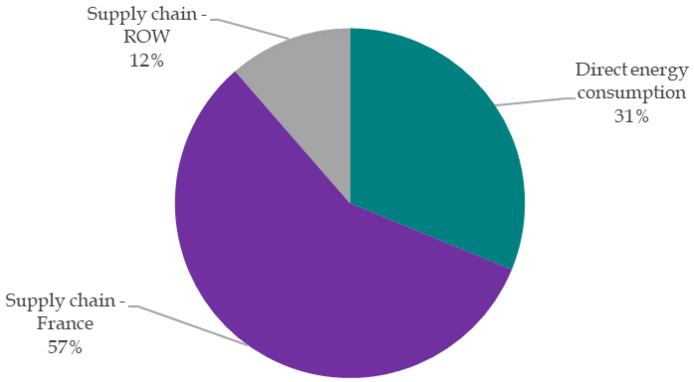


Figure 5.36 | Sources of the decrease in energy use in the first round of the second period, only residential, detailed version

Different from the simplified version of total budget, most of the energy savings occur in the supply chain in France. The top five products contributing to the energy decrease observed in the first round of the second period are presented in Figure 5.37.

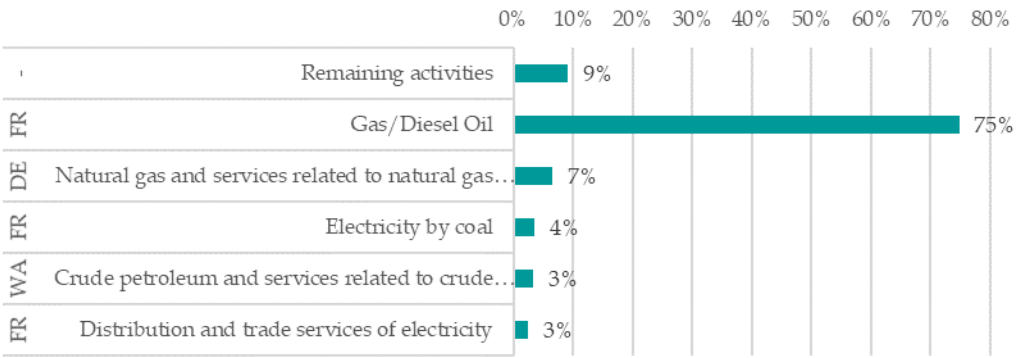


Figure 5.37 | Contribution of products to total energy saved in the first round of the second period, only residential, detailed version

As observed, the product presenting the highest contribution is the French gas and diesel oil, which is also the product the most affected by the perturbation, as shown as a reminder in Figure 5.38. Natural gas appears in the second place in Figure 5.37, also in line with the perturbation (Figure 5.38). French electricity by coal and electricity distribution and trade services are also in the top 5 contributors to the savings. Particularly with concern to the French electricity production by coal, it appears in this position due to the high energy intensity (the second highest energy intensity compared to all French products available in EXIOBASE). Crude petroleum from Asia and Pacific appears in the fourth position of higher contributors because it is the main input for French gas and diesel products, representing 18% of total inputs.

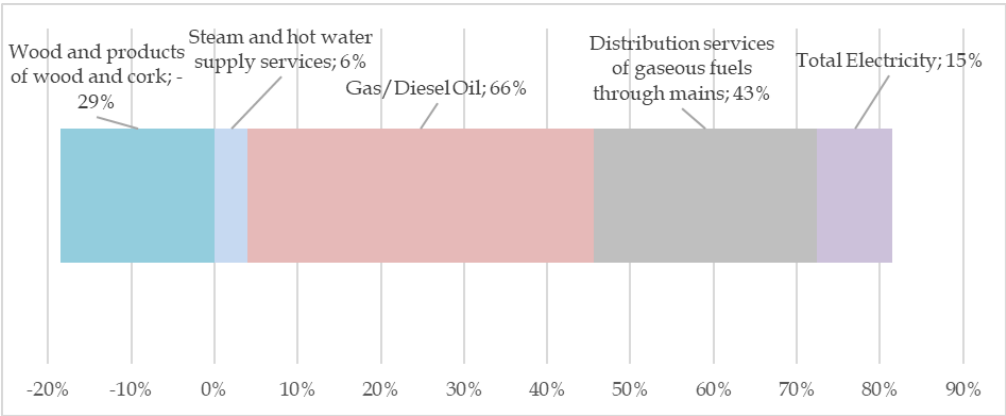


Figure 5.38 | Composition of the energy savings perturbation, only residential, detailed version

Wood products are represented by the wood chips, which are the only source of energy that has an increase in its use as a result of the Recovery Plan. However, it is not included in the energy consumption assessment since it is renewable and, here, the energy consumption indicator comprises fossil and nuclear energy use.

5.1.3.3 Only residential, simplified version

The cumulate energy use, round-by-round, of 'only residential, simplified version' is presented in Figure 5.39. The profile of the graph is very similar to "total budget, simplified version", observed in Figure 5.28. This similarity, already discussed in Section 5.1.1, is due to the assumptions for defining the exogenous perturbation.

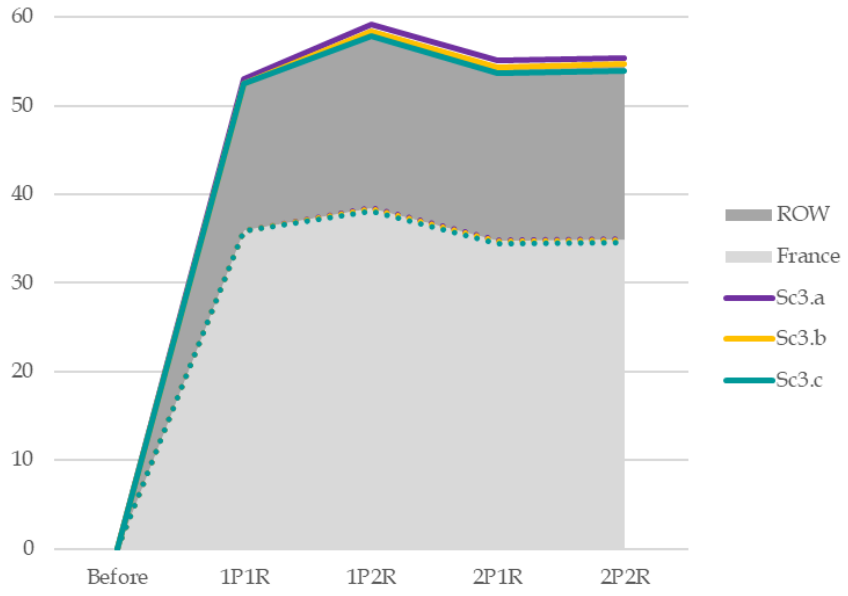


Figure 5.39 | Cumulative energy use, only residential, only residential, simplified version (PJ)

Scenario Sc3.a presents the highest cumulative energy consumption when compared with the other two scenarios, mainly because of the higher induced consumption in the first period. The values of energy use round-by-round are presented in Table 5.13.

Table 5.13 | Energy use, round-by-round, only residential, simplified version (PJ)

Scenario	1P1R	1P2R	2P1R	2P2R
Sc3.a	52.5	6.2	-4.1	0.3
Sc3.b	52.5	6.0	-4.1	0.3
Sc3.c	52.5	5.3	-4.1	0.3

When comparing these figures with the results obtained for the previous versions, the first round of the first period of this version has an intermediate value. This happens because of the same reason as for GHG emissions. In the second round, the energy use of this version is the highest one because this version has a higher multiplier effect than the detailed perturbation and higher magnitude than the total budget.

The contribution analysis follows practically the same proportions as the observed for the simplified version of the total budget. For example, concerning energy savings, direct energy consumption represented 65% of total savings, the energy use in the French supply chain represented 26% of total savings in the total budget. For this current version, direct

energy consumption represents 59% and French supply chain represents 31% of total savings, as presented in Figure 5.40. These differences are mainly due to the fact that public buildings do not use the same energy types for heating as those of residential buildings.

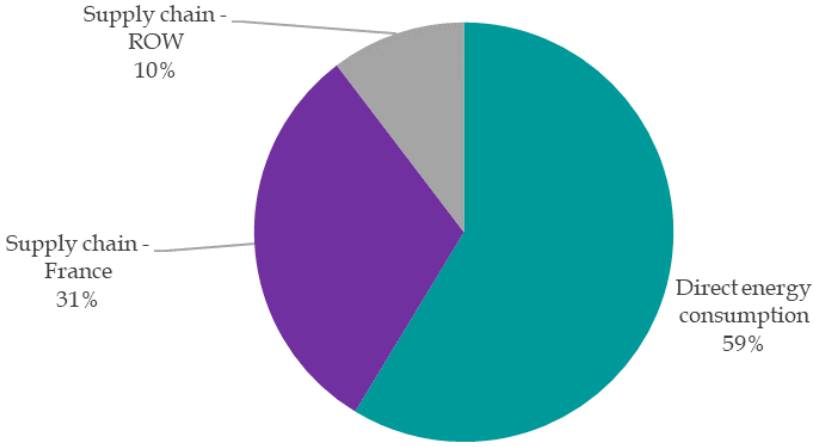


Figure 5.40 | Sources of the decrease in energy use in the first round of the second period, only residential, simplified version

5.2 Sensitivity analysis

A sensitivity analysis was conducted with the goal of understanding the influence concerning the technology approach used for obtaining the input-output tables (IOT). As explained in Section 3.3.1, the results presented in Sections 5.1 and 5.2 are based on the monetary IOT (MIOT) as it presents the most recent available economic data. However, the MIOT is built within partitioning allocation and for this reason, the first part of the sensitivity analysis focuses on changing the typology of the IOTs by using the hybrid IOT (HIOT). The latter is built using the "by-product technology" and it is more suitable for a consequential approach. Rather than comparing the modelling approaches, which are already discussed in the literature, the goal of this sensitivity analysis is to understand the potential differences that would be expected if more recent HIOT data were available (which is not the case at the moment of the thesis).

The increase in demand for construction works of 5.2 billion euros was assessed by using the hybrid version of EXIOBASE v3.3.18. The results for the GHG emissions were compared with the results obtained using the MIOT for the year of 2011 (Zenodo version, EXIOBASE 3.8.1), as presented in Table 5.14. For the MIOT results, the industry-by-industry data was used, which provides data with very similar level of aggregation as the hybrid version. For the Zenodo version, there are two possible environmental extensions, product-based accounting (PBA) and consumption-based accounting (CBA), as stated in Chapter 3.

Table 5.14 | Results of GHG emissions of the first round of the first period, for both hybrid and monetary IOT (kg CO2e)

2011	FR	ROW	Total
HIOT (2011)	5.47E+08	7.85E+08	1.33E+09
MIOT, PBA (2011)	5.53E+08	7.22E+08	1.27E+09
MIOT, CBA (2011)	1.50E+09	4.45E+08	1.95E+09

For comparison purposes, the GHG emissions of the first round of the first period using the MIOT from 2020 were 1.07E+09 kg CO_2e (see Table 5.1). The results obtained from HIOT are more similar to the MIOT results obtained from PBA extension. The results obtained with CBA are considerably larger than the other two types of datasets because they include embodied emissions in each activity, with possible overlaps. Another significant point is that as in CBA the imported emissions are already accounted in each product, the relative importance of the ROW is lower for these results when compared with HIOT and MIOT PBA.

The ten activities that contribute the most to HIOT's results are shown in Figure 5.41. When comparing these results with the ones presented in Figure 5.5, the first evident difference is the presence of the manufacture of basic iron, steel and ferro-alloys in the HIOT results. This category of products appear in five out of the top ten activities, while in the MIOT version, only Chinese and French manufacturing of iron and steel are among the ten activities with the highest emissions.

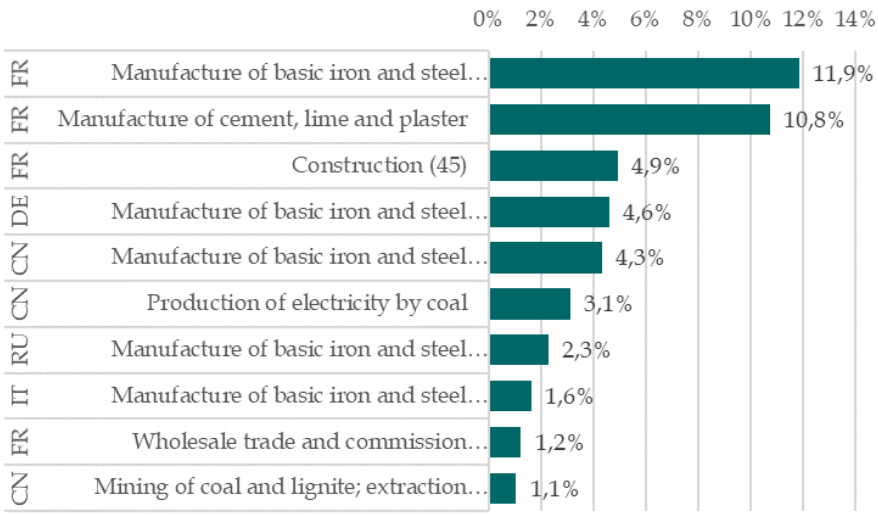


Figure 5.41 | Contribution of activities to total emissions in the first round, first period, HIOT

In the HIOT, French manufacture of "basic iron and steel and ferro-alloys" presents the 11th highest coefficient of hybrid amount of input per total output of construction works, while in the MIOT, it appears in the 24th position. This difference in classification is expected since the coefficients vary widely between both versions (hybrid units versus monetary units), but the difference in representativeness in relation to total emissions is due to a combination of factors. In HIOT, the GHG emission coefficient of basic iron, steel and ferro-alloys is very high

in comparison to the other products used in construction works, while in MIOT, the top activities present emission coefficients as high as the steel products.

Another possible reason for the difference is how the hybrid IOT is built (by-product technology), where the by-products are presented with a negative sign. For example, the activity "Re-processing of ash into clinker" presents a high contribution to the GHG emissions when using the MIOT (see Figure 5.42), while for the HIOT this product is considered as a negative input for the "manufacture of cement, lime and plaster" and thus it is a negligible contributor to total GHG emissions.

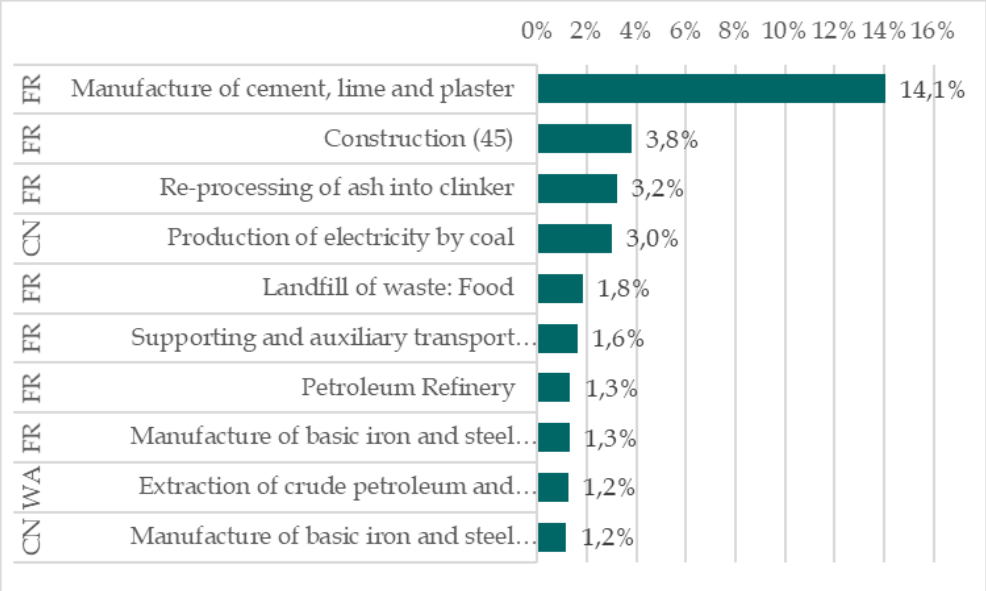


Figure 5.42 | Contribution of activities to total emissions in the first round, first period, MIOT (PBA)

5.3 Socio-economic impacts

The socio-economic impacts assessed in this thesis concern the pure redistributive effects, i.e., how the monetary (re)distribution affects the stocks of the institutional sectors, with a focus on households and the rest of the world. In the first rounds, the increase in deposits of households is only temporary since households will consume out of the received extra income. Therefore, the change in net wealth observed in the first round of each period is transitory and the actual change in net wealth must be accounted only at the end of each period. On the other hand, it might be interesting to analyze the changes in income round-by-round, mainly to understand the significant contributors to each round's increase and/or decrease.

In addition, when assessing income redistribution, it is essential to assess the impact on equality (the social profile) (Weidema, 2018). This is because earning additional money does

not affect all people equally, i.e., an additional unit of income has more utility for a lower-income person than for a higher-income one. Equity-weights can be used to weigh the income to reflect the marginal change in utility for each income group, using the elasticity of the marginal utility (ρ), as presented in equation 5.1.

$$VA_{w,i} = VA_i \times \left(\frac{Average\ income}{income\ of\ group\ i}\right)^{\rho} \qquad \text{Equation 5-1}$$

In this equation, the $VA_{w,i}$ corresponds to the equity-weighted income, for the income group "i", being low-skilled, medium-skilled, and high-skilled. The elasticity of the marginal utility (ρ) is obtained empirically from surveys based on individual happiness and life satisfaction vis-à-vis the household income. We use here the value provided by Layard et al. (2008), ρ=1.24, with a 95 % confidence interval of 1.14–1.35. The average annual income comes from wages and salaries and total employment provided by Exiobase.

Finally, a third point interesting that is to analyze concerns the loans taken out by French Government, to identify possible tensions created by the countries lending the money (financial transactions) versus the countries affected by changes in imports and exports (trade). For this, the ratio of loans granted by the country divided by the balance of trade for the given country is analyzed.

5.3.1 Total budget, simplified version

Changes in income and net wealth

The total changes in household income round-by-round, for the three scenarios, are presented in Table 5.15. The major changes occur in the first round of the first period (1P1R), where the households receive around €2.8 billion of income before paying taxes and social contributions. This amount is higher than the initial expenditure of households (2.0 billion), which must be carefully analyzed. One could say that if they receive more money than they spend, the financial aids are not needed. However, firstly, the money received from distribution comes from both expenditures: the one from the Government, where public buildings are retrofitted, and the one from households, where private buildings were retrofitted. Secondly, the households who spend the money are not the same who receive the extra income (see net wealth discussions further down).

Table 5.15 | Changes in households income, round-by-round, total budget, simplified version (MEUR)

	1P1R	1P2R	2P1R	2P2R
Sc1.a	2,767	459	-2	8
Sc1.b	2,767	462	-2	9
Sc1.c	2,767	394	0	5

The sources of revenue vary round-by-round, as presented in Figure 5.43. In the first round of the first period, the shares of each source of aggregate household income are the same for the three scenarios, which is why they are presented together in the figure. More than 90% of the household income changes due to the perturbation coming from wages in 1P1R. In the second round, there is a slight increase of the operating surplus contribution to total revenue of households, the proportion being practically the same for the three scenarios, meaning that the value-added of the products consumed in the second round presents a higher share of operating surplus when compared to the construction works.

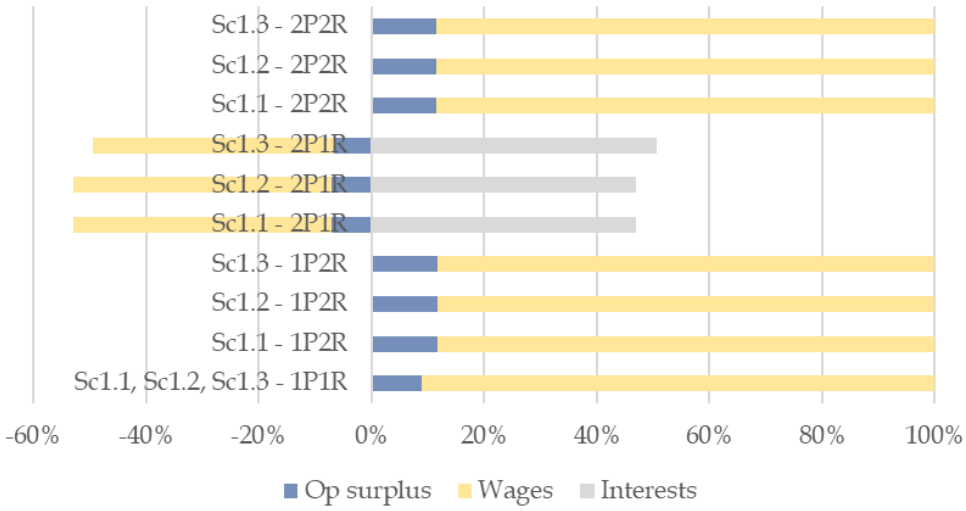


Figure 5.43 | Shares of each income type to total income of households, total budget, simplified version

In the first round of the second period, operating surplus and wages are negative because of the reductions in demand for energy products, causing a decrease in the workers' revenues. The interests received in this period are higher for Sc1.c because this scenario had the most increased deposits in the first period. The figure shows the shares for a better understanding of the weights of each income source, however, the totals are not the same for each scenario, as the income groups spending patterns are not the same.

The change in net wealth is simplified in the proposed model by the changes in deposits. This is due to the assumption that any net positive non-financial balance shift goes to financial corporations as deposits, and the negative changes are taken from the current account or financed by loans.

The deposit account from the transaction-flow matrix (TFM) is obtained at the end of each round. The deposit account represents the changes in income (property and labour) minus the expenditures. Table 5.16 presents the results of deposits made in each round for total households (all three scenarios) and for each income group (scenarios Sc1.a and Sc1.b). For scenario Sc1.c, the deposits are shown only for households in the aggregated form to be

comparable with the other scenarios. This is because in Sc1.c the income from operating surplus is received by households in its aggregated form, while for Sc1.a all income groups receive a share of the operating surplus and for Sc1.b, high-skilled households receive all operating surplus.

Table 5.16 | Change in deposits of households, total budget, simplified version (BEUR)

	1P1R				1P2R				2P1R				2P2R			
	HH	LS	MS	HS	HH	LS	MS	HS	HH	LS	MS	HS	HH	LS	MS	HS
Sc1.a	1.37	0.06	0.80	0.51	-0.71	-0.03	-0.44	-0.25	0.03	0.01	0.02	0.00	-0.01	0.00	-0.01	0.00
Sc1.b	1.37	0.05	0.68	0.64	-0.71	-0.02	-0.38	-0.31	0.03	0.01	0.02	0.00	-0.01	0.00	-0.01	0.00
Sc1.c	1.37				-0.61				0.03				-0.01			

In the first round of the first period (1P1R), there is an increase in total deposits of households, which is the same for the three scenarios. This increase in deposits results from an increase in income from labor, meaning that from the €5.2 billion from the Recovery Plan, €1.37 billion is distributed to households. In scenario Sc1.a, medium-skilled households receive 58% of total income and in scenario Sc1.b they receive 50%, so a significant part of the change in income comes from labor.

In the second round of the first period (1P2R), all changes in deposits are negative because households spend more money than they earn in the round. This happens because part of the money received in the previous round is only spent in 1P2R. In the first round of the second period (2P1R), the changes in deposits are again positive mainly because the energy savings reduce the energy bills. Another reason for the positive values is the property income from the interests received for depositing money in the previous period. Finally, in the second round of the second period (2P2R), the changes in deposits are for a second time negative for the same reason as in the first time, showing the importance of analyzing the balances at the end of each period, as presented in Figure 5.44.

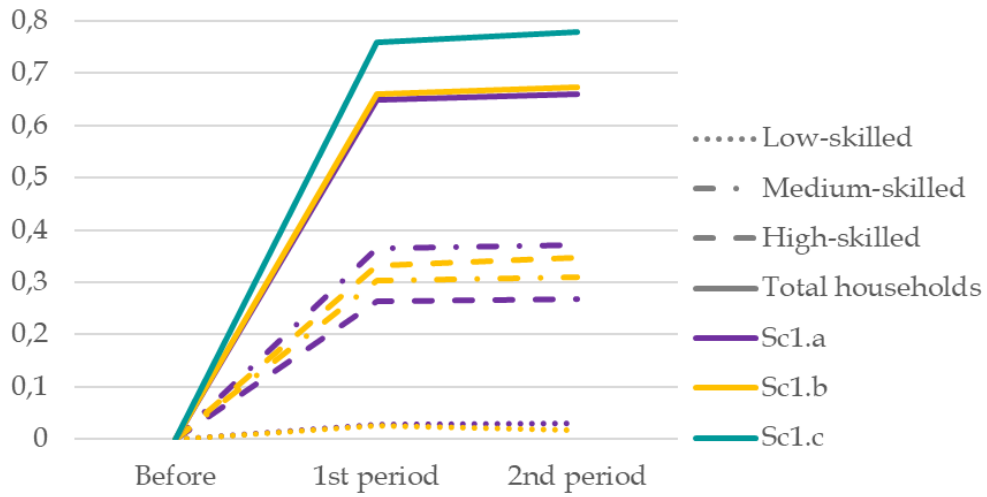


Figure 5.44 | Change in net wealth, round-by-round, total budget, simplified version (BEUR)

In general, the monetary distribution favors medium-skilled households, which receive more money than the other two income groups, for both Sc1.a and Sc1.b. In scenario Sc1.c the disaggregation among the three income groups is not possible, the results being thus presented for households in aggregated form. For this scenario, the net change in wealth is the highest one because all income coming from interests and operating surplus does not trigger any induced consumption, being saved. The bottom of the figure shows the low-skilled households' change in net wealth. This income group is the less favored by the Recovery Plan. A lower change in wealth of low-skilled households could be associated with less persons in this group. However, the calculations *per capita*, presented in Figure 5.45, show that low-skilled households also receive less money per person than the other income groups.

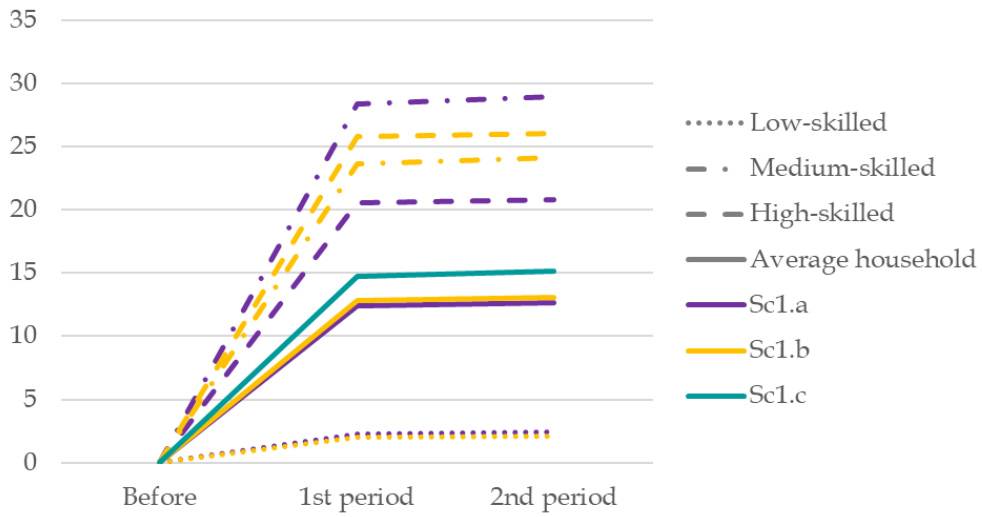


Figure 5.45 | Change in net wealth per capita, total budget, simplified version (BEUR)

Social profile

For obtaining the equity-weighted changes in net wealth by applying equation 5.1, the average income is considered to be 27,845 euros per worker. For low-skilled households, it is 8,340 euros per person, for medium-skilled 22,731 euros per person and for high-skilled it is 57,789 euros per person. The equity weighted net wealth results calculated using Equation 5.1 and the values mentioned above are presented in Table 5.17.

Table 5.17 | Equity-weighted changes in net wealth, total budget, simplified version (BEUR)

	1P1R				1P2R				2P1R				2P2R			
	HH	**LS**	**MS**	**HS**	**HH**	**LS**	**MS**	**HS**	**HH**	**LS**	**MS**	**HS**	**HH**	**LS**	**MS**	**HS**
Sc1.a	1.50	0.26	1.03	0.21	-0.79	-0.13	-0.56	-0.10	0.05	0.03	0.02	0.00	-0.03	-0.02	-0.01	0.00
Sc1.b	1.36	0.22	0.88	0.26	-0.73	-0.11	-0.49	-0.12	0.05	0.03	0.02	0.00	-0.03	-0.02	-0.01	0.00

Since changes in net wealth disaggregated by income level are only considered in the Sc1.a and Sc1.b, Sc1.c is not presented in the table. The total net wealth is higher when equity-weighted by utilities; the difference is more evident for scenario Sc1.a, which shows a 7% increase in total net wealth change in the first period compared to the unweighted results. The

observed increase is not as substantial as the medium-skilled, the most benefitted income group, whose weighting factor is close to one. However, there is a shift in the results of low-skilled and high-skilled, as observed in Figure 5.46. In Figure 5.44, low-skilled households appeared at the bottom of the graph, while in the equity-weighted (Figure 5.46), the high-skilled dropped to the bottom of the chart. In addition, scenario Sc1.a presents the highest utility when compared with Sc1.b.

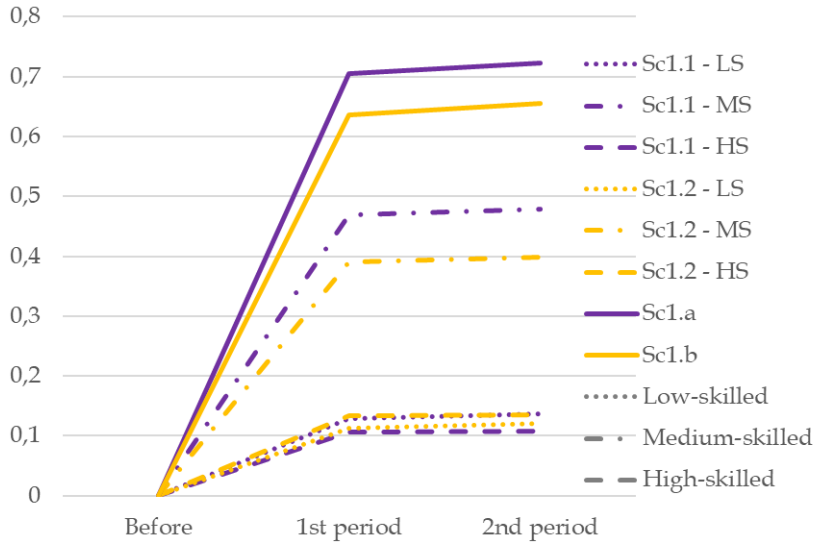
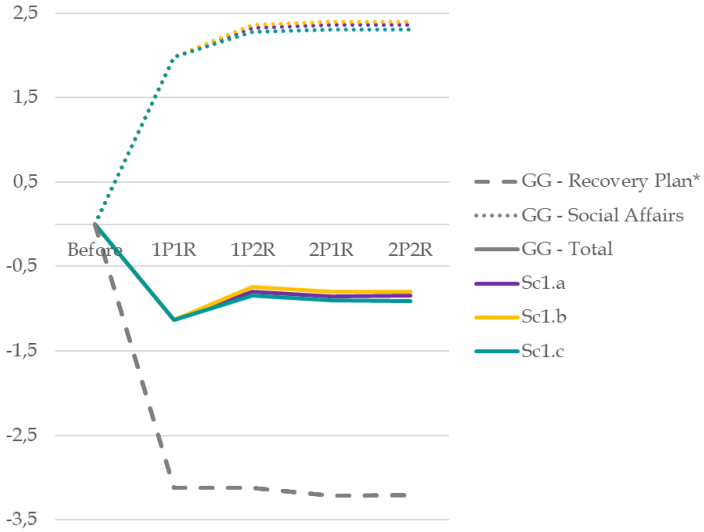


Figure 5.46 | Equity-weighed changes in net wealth, total budget, simplified version (BEUR)

Changes in stocks of other institutional sectors

In the simplified version, the households increase their net wealth (see Figure 5.44) since all the money spent on retrofitting is agreed to by the Government. As the Government finances the retrofitting works, this institutional sector has been indebted since the beginning, as presented in Figure 5.47.



(*) GG- Recovery plan presents the same values in all rounds for the three scenarios

Figure 5.47 | Changes in the net wealth of the French General Government, total budget, simplified version (BEUR)

In this figure, the activities of the General Government concerning the recovery plan are at the bottom of the chart, showing that these activities represent the highest decrease in the net wealth of the general Government. On the other hand, Government social affairs increase their net wealth (at the top of the chart) as they receive money from taxes and operating surplus as a consequence of growing economic activities. The decrease in net wealth coming from recovery plan activities offsets the increase in net wealth seen for social affairs. This means that the overall balance for the Government is negative over the distribution periods, and they are in debt at the end of the second period.

Both financial and non-financial corporations increase their net wealth, but not with the same patterns, as shown in Figure 5.48. The changes in the net wealth of non-financial corporations are shown on the left side of the figure (a). These results follow the pattern observed for environmental impacts, with the most significant increase in wealth occurring in the first round of the first period, followed by a relevant increase in the second round, and then remaining stable for subsequent rounds of distribution. Scenario Sc1.b presents the highest change in net wealth for this institutional sector because of the consumption patterns of the medium-skilled households, which consume more in this scenario when compared with the other two scenarios.

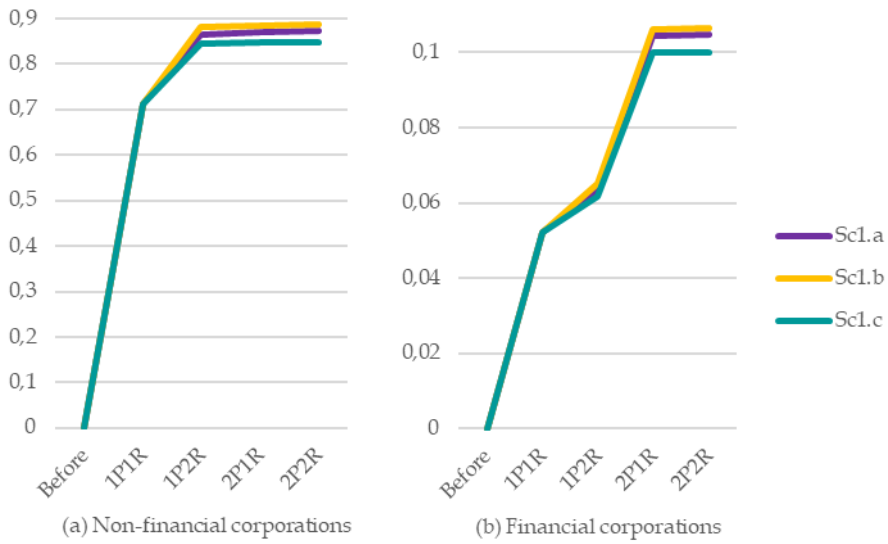


Figure 5.48 | Changes in the net wealth of (a) non-financial corporations and (b) financial corporations, total budget, simplified version (BEUR)

The right side of the figure (b) presents the changes in the net wealth of financial corporations. As the latter has a substantial share of their income coming from interests, the increase in wealth in the first round of the second period (2P1R) is more evident for this institutional sector. Scenario Sc1.c presents the lower growth in net wealth because financial corporations have to pay more interest on household deposits, as households have saved more money in this scenario.

Financial balances *versus* trade effects

The debt created by the Government to finance the Recovery Plan is made through loans taken out one part from residents, i.e., French institutional sectors, and the other part from non-residents. We are able to know who lends money to the French general Government from the Stocks database. Figure 5.49 presents the ratio between the amount of money lent to the French Government divided by the results of the change in the balance of trade for each country. For example, Japan lent €368 million to the French Government and has a balance of trade of €12 million, presenting a ratio of 30. On the other hand, Spain lends €46 million to France and shows a balance of trade of €73 million, with a ratio of 0.6. The countries with the higher ratios benefit less from the policy, with the resulting possibility of leading to tensions.

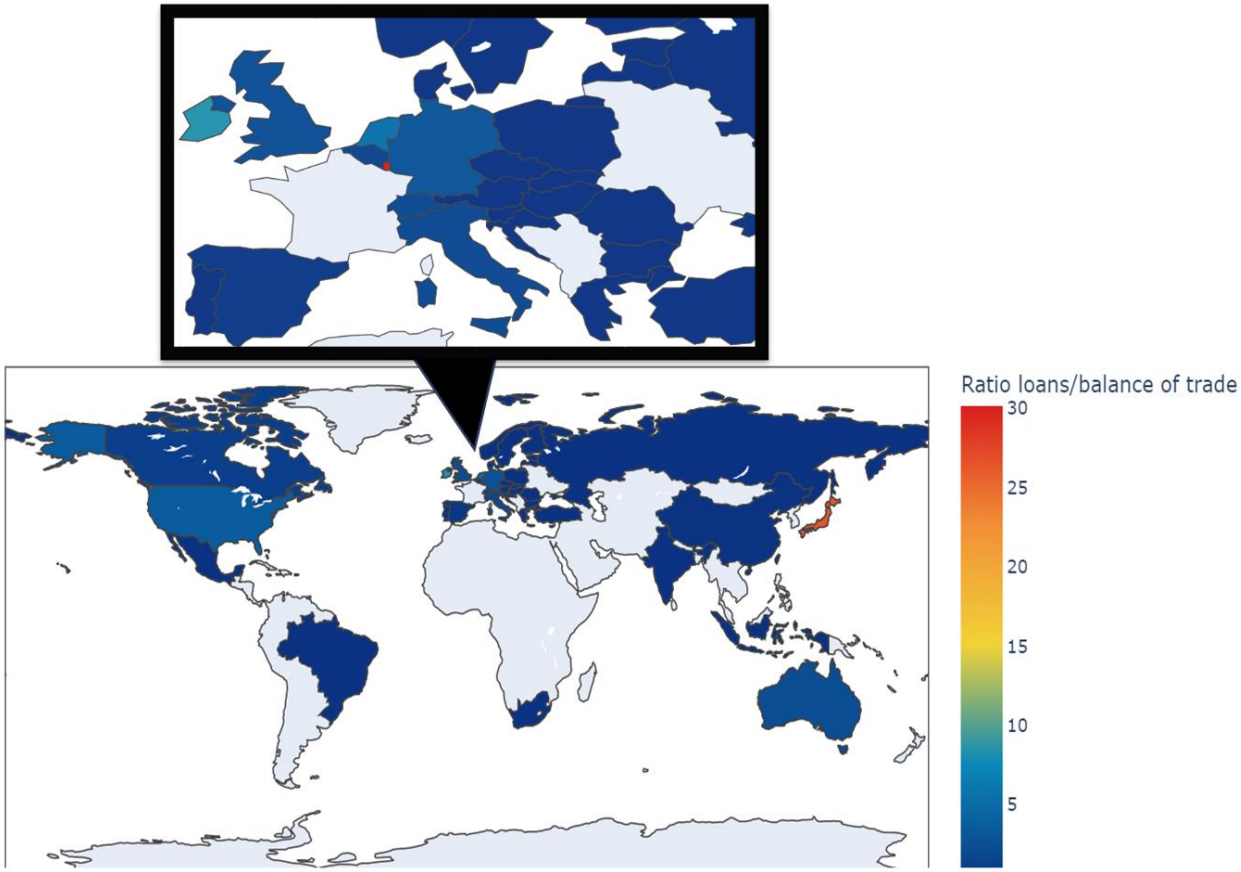


Figure 5.49 | Ratio of loans granted per unit of balance of trade, by country, total budget, simplified version

Japan lent €368 million to the French Government and has a balance of trade of €12 million, presenting a ratio of 30. On the other hand, Spain lends €46 million to France and shows a balance of trade of €73 million, with a ratio of 0.6. Luxembourg, Japan and Ireland present the highest ratios, meaning that they contribute significantly to the loans taken by France (or they contribute to finance the Recovery Plan) but do not benefit from trade. High ratios might be an indication of possible tensions.

Another interesting point to analyze is how GHG emissions are linked to the money received from trade, i.e., how vulnerable some countries might be due to the policy established in France. For that, the intensity figure of total GHG emissions divided by the total money received from trade (exports *minus* imports) is presented in Figure 5.50.

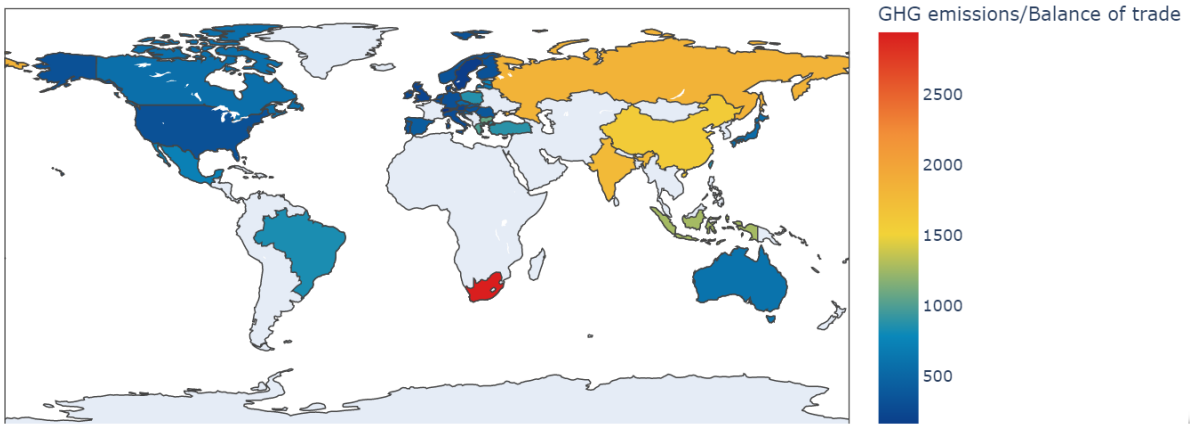


Figure 5.50 | GHG intensity per net received money (tCO2e/MEUR)

As observed in the chart, South Africa, Russia, India, China and Indonesia have the highest emissions for the money received. This is an indication of the displacement of emissions due to the lower prices, which reinforces the importance of taking into account indirect emissions in new policies.

5.3.2 Only residential, detailed version

In the detailed version of thermal retrofitting works conducted in residential buildings, when households start conducting their thermal retrofitting projects they become indebted as part of the money used to finance their projects comes from loans (assumption presented in Chapter 4). Therefore, their changes in wealth are negative as presented in Figure 5.51.

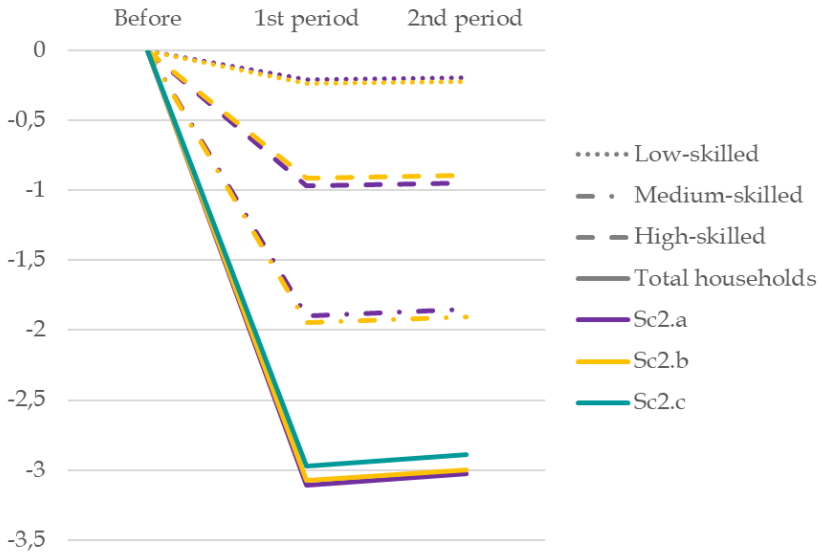


Figure 5.51 | Changes in net wealth, only residential, detailed version (BEUR)

Low-skilled households are the least indebted income group because they are the ones who conduct less thermal retrofitting works. One possible reason for this is that the change in MPR due to the Recovery Plan involves opening the financial aids to all French residents, therefore the marginal affected income groups are medium and high-skilled, as low-skilled were already aided by MPR before the Plan.

Medium-skilled households are the most indebted income group as they spend around 60% of total thermal retrofitting budget. Their decrease in net wealth is not compensated in the second period by the saved money from energy bills, which is expected as presented in Section 4.2.2.

For both low and medium-skilled groups, Sc2.a presents the lowest decreases in net wealth, as in Sc2.b high-skilled households receive all the money from the operating surplus. This shows that operating surplus play a non-negligible role in the income of households, being necessary to conduct further research to better understand the mechanisms associated with the distribution of this money in new policies.

From the second period and so on, part of the money spent on the first period is recovered as they pay less on energy bills. Theoretically, if they keep saving energy and consuming out of their changes in income, they would recover the money invested on thermal retrofitting works on average in 28 years, or from 20 years for low-skilled households to 35 years for medium-skilled households.

Social profile

The social profile of the Recovery Plan was also assessed following the procedure presented in the beginning of this section. Figure 5.52 presents the results for the detailed version.

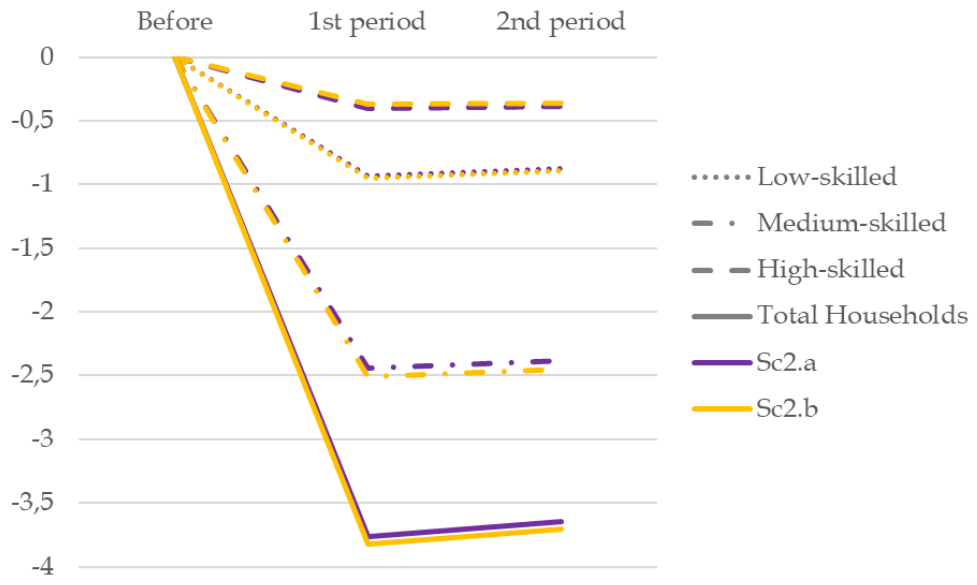
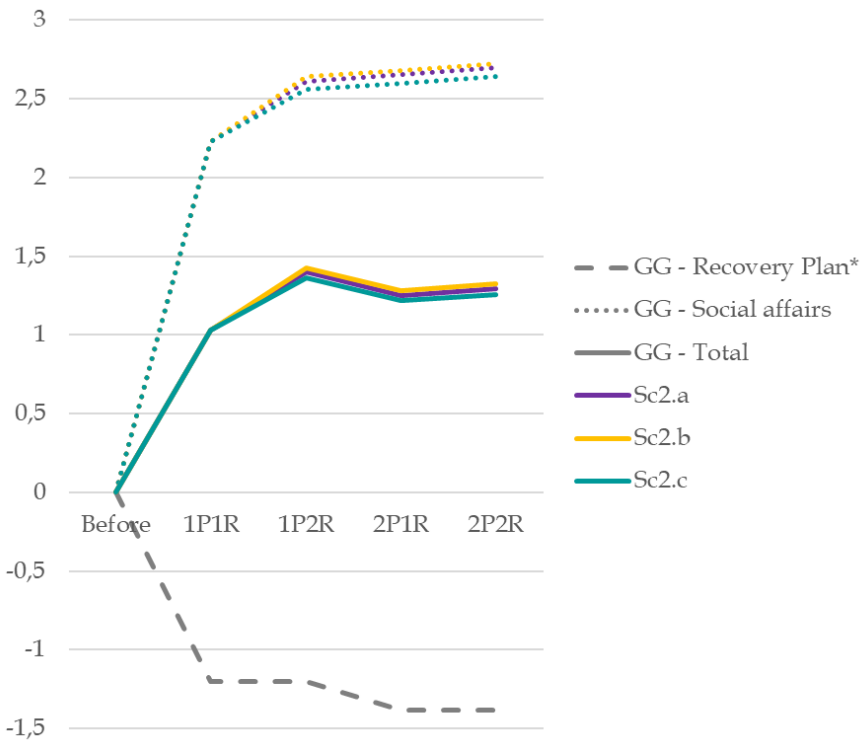


Figure 5.52 | Equity-weighted changes in net wealth of households, only residential, detailed version (BEUR)

Taking out an additional euro from the wealth of low-skilled households has a higher impact than for the high-skilled households, justifying the switch in position of these two income groups compared with the changes in net wealth of Figure 5.51. Moreover, scenario Sc2.a presents a higher utility when compared with scenario Sc2.b, so that concentrating the money from operating surplus to high-skilled income group is less effective from the social utility point of view.

Changes in stocks of other institutional sectors

General Government, on the other hand, is in a positive position from the first round of the first period until the end of the second period, as shown in Figure 5.53. It is important to highlight that the interest free loans accorded by the Government to households do not affect the wealth of the latter in the first period as they do not spend any money at the beginning. From the second period and so on, the Government pays the interests on the loans taken in the first period by households and then the wealth of the GG-RP drops in 2P1R. This drop is larger than the increase in wealth of the social affairs (from the monetary re-distribution taxes, operating surplus, etc.), which justifies the net decrease in Government at the end of the second period relative to the first period.



(*) GG- Recovery plan presents the same values in all rounds for the three scenarios

Figure 5.53 | Changes in net wealth of the general Government, only residential, detailed version (BEUR)

For both financial and non-financial corporations, the increase of net wealth is more significant in the detailed version than in the simplified version, but follow the same patterns as Figure 5.54 shows. The difference from the simplified version is because the exogenous perturbation is lower in the latter so, as the surplus is proportional to the increase in production, the increase in wealth is also lower.

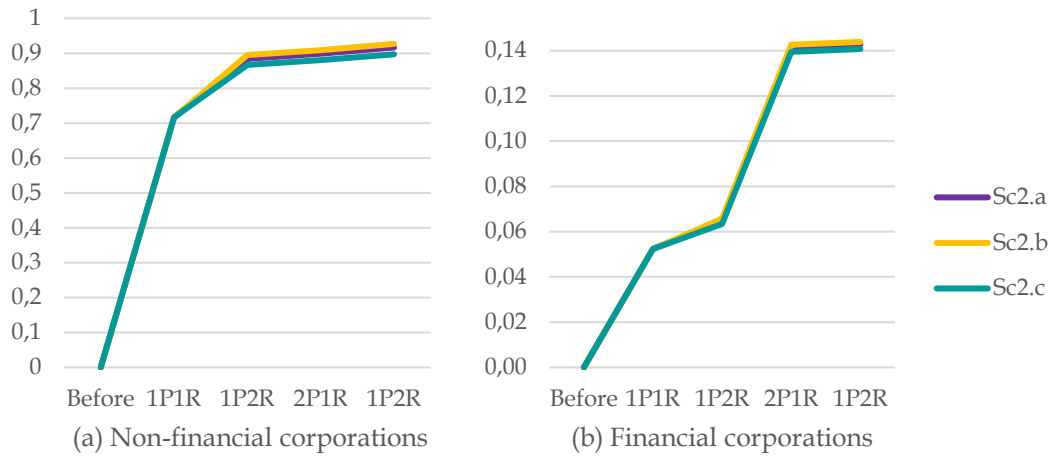


Figure 5.54 | Change in net wealth of (a) non-financial corporations and (b) financial corporations, only residential, detailed version (BEUR)

Financial balances *versus* trade effects

The results obtained with the detailed version of the exogenous perturbation do not differ significantly from the ones from the simplified version. With regard to the ratio between loans granted by each country to the French Government in relation to the result of trade balance (induced exports minus induced imports), the results are presented in Figure 5.55.

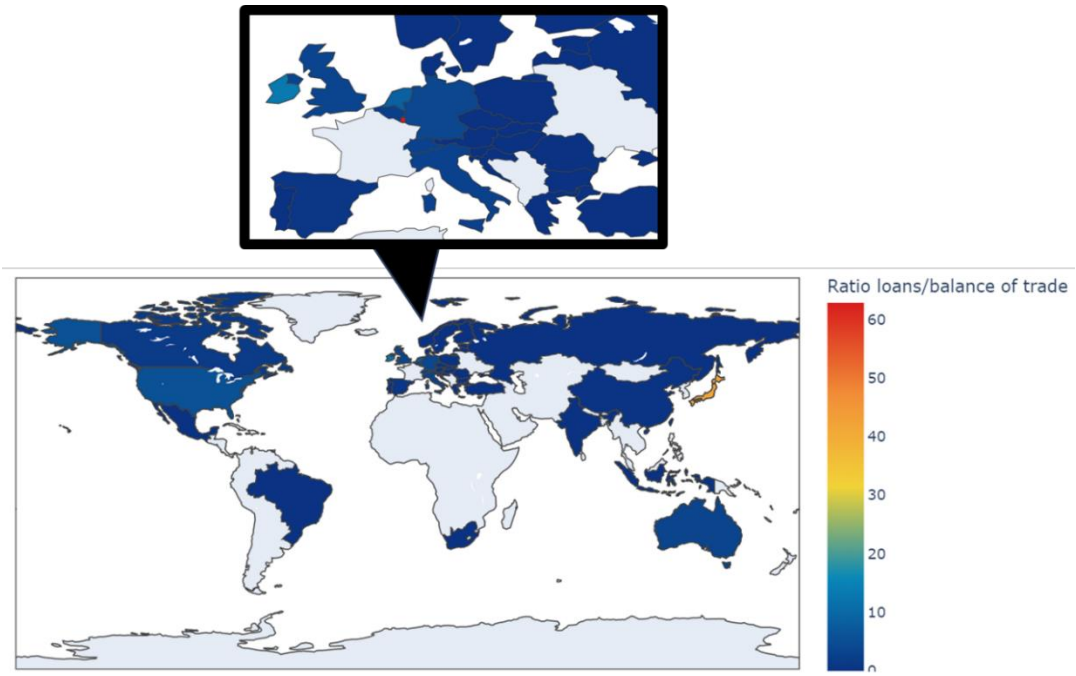


Figure 5.55 | Ratio of loans granted per unit of balance of trade, only residential, detailed version

The highest ratios are observed for the same countries as in the simplified version, i.e., Luxembourg, Japan and Ireland. However, the values of the ratio for the detailed version are, on average, three times lower than the values obtained for the simplified version. The main reasons for that are, first, that the Government takes out more loans in the simplified version as the totality of the Recovery Plan is included in the scope of the study (residential plus public buildings), while only residential buildings are taken into account in the detailed version. Second, even considering that the detailed version only covers the residential buildings, the exogenous perturbation is higher than the one of the simplified version as it is more realistic in terms of actual costs for households (i.e., the Recovery Plan only covers a part of the thermal retrofitting costs). Therefore, in the simplified version, the loans granted by the countries are higher while the balance of trade is similar to the detailed version as the exogenous perturbation is not so different, resulting then in higher ratios.

5.3.3 Only residential, simplified version

In the simplified version of thermal retrofitting works conducted in residential buildings, households are indebted since the beginning of the first period as part of the money used to finance their projects comes from loans (assumption presented in Chapter 4). This is the same assumption as the one made for the detailed version. Therefore, their changes in wealth are negative as presented in Figure 5.56.

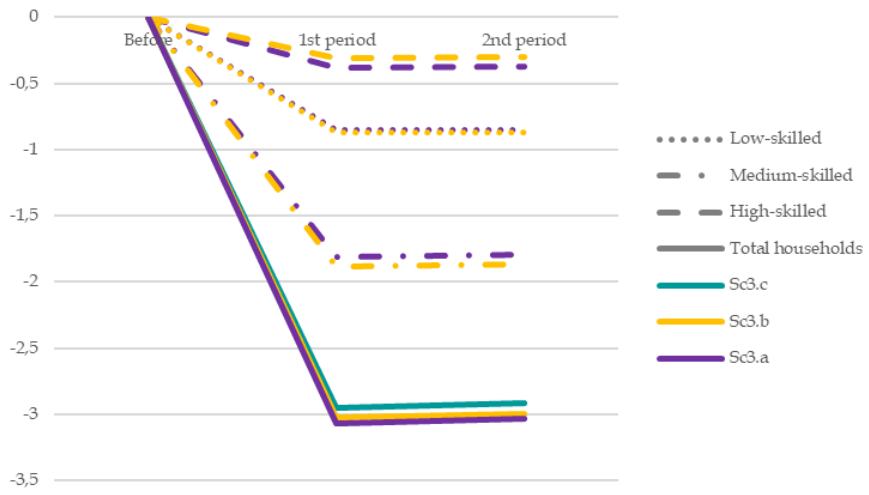


Figure 5.56 | Changes in net wealth, only residential, simplified version (BEUR)

When comparing with the detailed version of the budget for residential buildings, where low-skilled households were the least indebted income group, in this version, high-skilled HHs are the least indebted ones for both scenarios Sc3.a and Sc3.b. This is because, in this simplified version, low-skilled HHs double their expenditure in relation to the detailed version, while receiving the same financial aid as for the detailed version. The reason for that

is that the simplified version considers the expenditure of on thermal retrofitting works is proportional to the money received from financial aids. On the other hand, in the detailed version, the expenditure by income group is taken from MENFIS. The simulations indicated that high-skilled households spend in a higher proportion than the received financial aid, so in the simplified version they spend less and earn basically the same money from the monetary distribution. This justifies their higher net wealth in this version when compared to the previous one.

For both low and medium-skilled groups, Sc3.a presents the lowest decreases in net wealth, showing that operating surplus represents a fairly significant part of households income.

The increase in net wealth observed in the second period is not significant for none of the income groups. They would take from 45 years (high-skilled HHs) to 171 years (low-skilled HHs) to recover the decrease in wealth from their loans taken out in the first period. The results of the social profile for this version are very similar to those of the simplified version.

Concerning other institutional sectors, the general government increases the net wealth round-by-round, as presented in Figure 5.57. The main difference of these results in relation to those of the detailed version is that the second round of the second period has a more significant increase in the detailed version because the latter presents higher induced consumption as households save more money from reduced energy bills.

(*) GG- Recovery plan presents the same values in all rounds for the three scenarios

Figure 5.57 | Changes in the net wealth of the French General Government, only residential, simplified version (BEUR)

No significant change is observed in the graphs obtained for the other institutional sectors in relation to those of the detailed version. For this reason, no further analysis is presented here. The graphs and tables are provided in Appendix 6.

5.4 Final discussions

5.4.1 GHG emissions *vis-à-vis* the French Low Carbon National Strategy

The Low Carbon National Strategy (LCNS) sets the goal for the residential and tertiary sector to present, in 2030, annual emissions of 45 $MtCO_2e$, considering that the emissions of the sector in 2015 were 88 $MtCO_2e$. This means a theoretical annual average reduction of 2.87 $MtCO_2e$. For achieving the target, the LCNS also proposes 'carbon budgets', presenting specific targets for each sector based on a period of 5 years. This notion can be appropriated for analyzing the thermal retrofitting policy because there is an increase in emissions justified by the potential reduction in emissions in the following years. For this reason, the results obtained in this thesis are compared with the current carbon budget, which covers the period from 2019 to 2023. The target set for this carbon budget is annual emissions of 422 $MtCO_2e$, of which, 78 $MtCO_2e$ are attributed to buildings.

The recovery plan was signed in September 2020, therefore, the measures are considered to start taking place in 2021. Considering that the emissions reduction are kept the same from 2022 to 2023, the results of the French GHG emissions for the three versions of the perturbation for the period from 2019 to 2023 are presented in Figure 5.58. The results presented in the graph concern the first-order effects, which are the same for the three scenarios in each version.

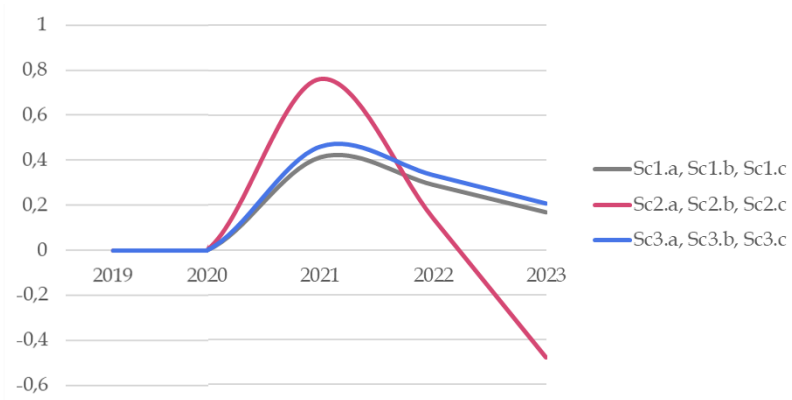


Figure 5.58 | French GHG emissions from 2019 to 2023 due to the recovery plan (MtCO2e), only first-order effects

The results presented in Figure 5.58 (above) show that, for the simplified versions, the energy reductions do not offset the initial increase, while for the detailed version of residential buildings the energy savings compensate the initial increase in the first half of 2022. However, even considering that for the simplified versions the reductions do not compensate the initial increase in emissions within the period of the carbon budget, the period emissions represent less than 0.1% of the total budget attributed to buildings.

As presented in Section 5.1.1, second-order effects are fairly significant when compared with the first-order effects. However, including these emissions in this comparison with the LCNS targets can be tricky since the changes in emissions resulting from the economic perturbation affect a different sector at a time. For example, the increase in emissions observed in the first round of the first period contribute to the emissions of the construction industries (affecting the industry sector), while the emission reductions affect the residential and tertiary sector.

Considering these intersections between the reduction targets and the sectors that are actually affected by the policy, the increase observed in the first round of the first period is also compared with the magnitude of the LCNS reduction target established to the industries. This is due to the fact that, at the beginning, the plan triggers an increase of emissions while the target consists of an emission reduction. For the industries sector, the LCNS sets the goal of annual emissions of 53 $MtCO_2e$ in 2030, considering annual emissions of 81 $MtCO_2e$ in 2015, resulting in an average annual decrease of 1.87 $MtCO_2e$. Therefore, the increase observed in the first round of the first period represents 58% of the industries' target for the simplified version, and 96% of the industries target for the detailed version.

The second round of the first period affects the whole French economic sectors, so that, the comparison with the target of any sector in particular is less relevant. Therefore, the second round of first period emissions represents from 4.2% (scenario Sc1.c) to 4.5% (scenarios Sc1.a and Sc1.b), for the simplified version, and from 5.0% (scenario Sc2.c) to 5.3% (scenarios Sc2.a and Sc2.b), for the detailed version, of total annual reductions of France.

5.4.2 Wastes and circular economy

The wastes assessed in this thesis are the amounts of produced waste that could potentially be supplied as secondary raw material to produce products or energy. As the waste flows are not available in the pymrio version, the waste production intensities from the environmental extensions available on the hybrid version were used for estimating the wastes production, meaning that the proportions of produced waste by product were kept the same as from 2011. The results presented in Section 5.1.2 show that waste production is the only indicator in which the energy savings do not compensate any part of the additional production of equipment and materials at the beginning of the Program. The results also show a high contribution of waste production in the rest of the world.

In the simplified version, where only construction works are affected by the economic perturbation, most of waste is produced in the ROW (more than 80% for the three scenarios). From part of wastes produced in France in the first round of the first period (111 ktons), wood wastes are by far the most produced ones (64 ktons), mainly by the construction products (71%). Ashes are the second most produced type of waste in France as a result of the first round of distribution (11 kton), which are employed to produce clinker, a raw material for cement in the construction sector.

From the EXIOBASE waste dataset it is possible to identify some significant points. The first is the relationship between the wood wastes supplied and used in France, which, for France, is lower than one, meaning the French activities consume more wood wastes than they produce. The second point is that the re-processing of secondary wood material into new wood material corresponds only to 20% of total use in France, while 41% is incinerated, and 39% goes to a landfill. For the construction wastes, the re-processing of secondary construction material into aggregates also corresponds to 20% of total use in France, the remaining part goes to a landfill. These figures show an important opportunity to foster circular economy activities in the country.

5.5 Conclusions

5.5.1 GHG emissions, energy consumption and waste production

This chapter studied three environmental categories, namely GHG emissions, energy consumption and waste production for three versions of the economic perturbation regarding the French recovery plan. The results of the three versions present some similarities, as can be observed in Figure 5.59. The first point is that, in the three versions, the environmental consequences were more significant in the first round of the first period; however, the induced consumption occurring as a result of the income redistribution is non-negligible for the three impact categories assessed. The second point in common is that the consequences occurring in the ROW follow similar patterns for the three versions.

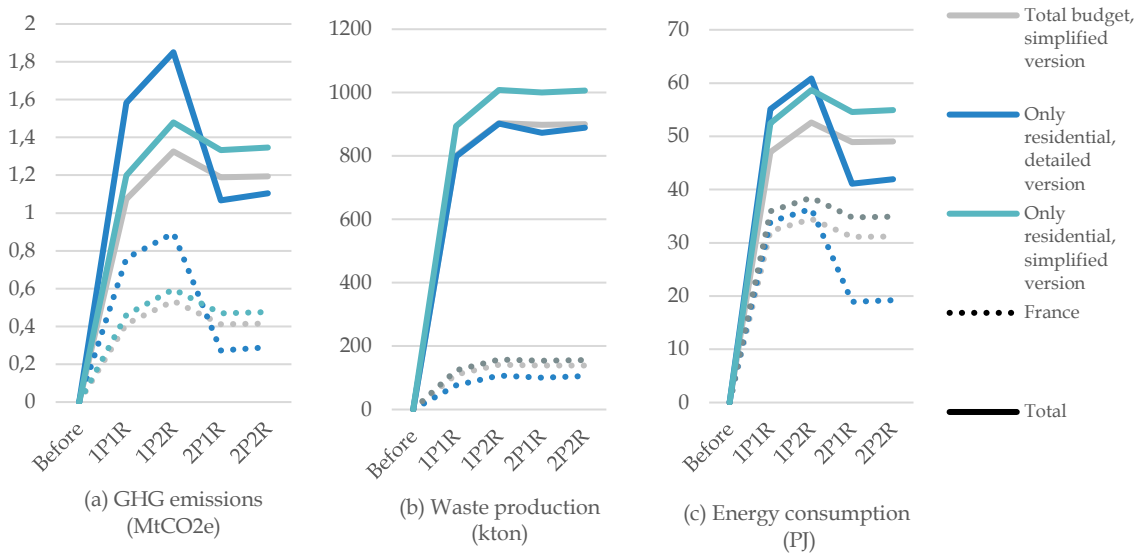


Figure 5.59 | Total results of environmental consequences for the three versions

With regard to the first point, as presented in sections 5.1, 5.2 and 5.3, the induced consumption represents from 20% to 23% (both simplified versions) and from 15% to 17%

(detailed version of residential buildings retrofitting works) of first order GHG emissions. Concerning energy use, the induced consumption represents from 10% to 12% (both simplified versions) and from 9% to 10% (detailed version of residential buildings) of first order effects. Finally, concerning waste production, the second order effects represent from 11% to 13% of first order waste production, for the three versions. This means that the second-order effects are fairly significant and need to be taken into account in new policies.

The environmental consequences occurring in the rest of the world are paramount for the three environmental issues analyzed here, notably for waste production. For the latter, 86% (both simplified versions) and 90% (detailed version of residential buildings) of total wastes produced in the first round of the first period are from foreign activities, mainly precious metal ores and concentrates from Asia, America and Africa in the three versions. The wastes produced from the induced consumption are also higher in the ROW than in France, however, it drops to around 70% of total waste production for the three versions.

The GHG emissions occurring in the ROW are also substantial for the two rounds of the first period. In the first round, they represent 62% (both simplified versions) and 52% (detailed version of residential buildings) of total emissions. In the second round, they represent around half of total emissions for the three versions. Among the assessed foreign countries and regions, German and Chinese products are the most affected ones (presenting the most significant change in total output). Chinese electricity by coal and basic iron and steel are presented among the top 10 activities contributing to total GHG emissions.

The ROW contribution is less significant for energy consumption than for the other two indicators. In the first round of the first period, the ROW energy use represents from 32% (both simplified versions) to 38% (detailed version of residential buildings). In both simplified versions (total budget and only residential), more than half of the energy use in the first round of the first period is from French construction works, justifying the lower contribution of ROW activities. In contrast, in the detailed version of residential buildings, the embodied energy of French machinery equipment, rubber and plastic products and other non-metallic mineral products represent around 45%. Moreover, German natural gas and services appear among the top 5 activities for both versions because of their high embodied energy and significant change in output in relation to the total.

The main difference between the simplified versions and the detailed version lies in energy savings accounting. The GHG emissions and energy consumption drop observed in the second period is more evident in the detailed version, as the calculations were obtained from the econometric model rather than estimated based on the savings in energy bills (simplified version). Table 5.18 presents the time needed to compensate the GHG emissions, energy consumption and waste production occurring as a result of the increase in demand for products and equipment (1P1R) and also the induced consumption (1P2R). The calculations considered that each year presents the same reductions in emissions, energy consumption and waste production as the ones in the first round of the second period.

Table 5.18 | Compensation of extra GHG emissions, energy consumption and waste production from the increase in demand (in years)

Version	Boundary	GHG emissions	Waste production	Energy consumption
Total budget, simplified version	France	3.4	41.3	9.5
	ROW	44.2	240.1	45.9
	Total	7.8	144.1	12.7
	Total 1P1R and 1P2R	9.4	162.4	14.2
Only residential, detailed version	France	1.2	11.9	1.9
	ROW	5.1	32.2	9.4
	Total	2.0	27.7	2.8
	Total 1P1R and 1P2R	2.4	31.3	3.1
Only residential, simplified version	France	3.6	33.0	9.8
	ROW	37.9	187.7	39.0
	Total	8.2	113.9	12.8
	Total 1P1R and 1P2R	9.9	128.4	14.3

The time needed to compensate for the environmental impacts occurring in the first period varies considerably between the simplified versions and the detailed one, and also among the environmental categories. For the simplified versions, the GHG emissions occurring in France are compensated in 3.4 years for the total budget and 3.6 years when considering only residential buildings, while in the ROW they are compensated from 37.9 years (only residential) to 44.2 years (total budget), showing a strong amount of imported emissions. When combining the emissions occurring in France and those in the ROW, the time needed to compensate the first order emissions is around 7.8 years for the total budget and 8.2 years for the residential budget, which are increased to 9.4 years and 9.9 years, respectively, when also considering the induced consumption.

The time for compensating for the increase in production of waste in France is 33 years for the simplified version of the budget dedicated to residential buildings and 41.3 years for the total budget, growing to 188 years and 144.1 years, respectively, when combining waste production in France and in the ROW. The total budget presents a lower time compared to only residential buildings for waste production because residential buildings use more solid energy sources (wood chips), resulting in higher reductions than for the total budget (public and residential buildings).

For energy consumption, the simplified version of the total budget shows that 9.5 years are needed to compensate the energy consumption increase for producing the equipment and insulating products occurring in France. When considering total energy consumption happening in France and in the ROW, the time needed to compensate for the initial

consumption increases to 12.7 years and to 14.2 years when also considering the induced consumption (1P2R). The results of the simplified version of residential buildings are not significantly different from those of the total budget.

For the detailed version, the time needed for compensating for the environmental impacts observed in the first round is reduced for all cases to less than 10 years for energy consumption and GHG emissions. This is mainly because the energy savings are more significant in this version. For waste production, however, the time needed to compensate for waste production in France and worldwide is more than 10 years. These findings reinforce the importance and urgency of effective circular economy policies.

Sensitivity analysis has shown that changing how the processes are linked have an importance on the results. Therefore, ideally it would be necessary to use an up-to-date hybrid IO table and build a monetary equivalent to run the model developed in this thesis.

5.5.2 Socio-economic impacts

On the socio-economic side, in the simplified version of the total budget, we were interested in analysing how the extra money coming from the European Union and from loans taken out by French Government to finance the French Recovery Plan would affect the wealth of the French institutional sectors. Therefore, the injected money was considered as the total budget for public and private residential buildings, i.e., €5.2 billion. This extra money only pays for one part of the thermal retrofitting works; however, the actual money spent on retrofitting was not taken into account in the simplified version as it was not the focus of the analysis. On the other hand, in the detailed version, the study scope only covered the residential buildings, i.e., an increase in financial aid of €2 billion, but the information on how much money was actually spent on thermal retrofitting works was taken into account. Therefore, the exogenous perturbation for the detailed version was €5.8 billion, where €2 billion come from financial aid and €3.8 billion come from household stocks. A third version of the perturbation was built to compare the approaches adopted in the previous versions, where only residential buildings were studied by simplifying the foreground affected activities.

Therefore, the three exogenous perturbations are not significantly different in magnitude, so the money circulating within the economy is €5.2 billion for the simplified version of the total budget and 5.8 billion for both versions studying only residential buildings (simplified and detailed). The main difference between the "total budget" and "only residential" versions lies in who pays for this money and from where the money is taken, having thus an important effect on the socio-economic impacts. The results presented in this chapter show that households decrease their net wealth since the beginning of the Recovery Plan if they need to finance a part of the works from their own stocks. In contrast, when the

government funds the global household expenditure, they increase their net wealth round-by-round, also benefitting from the money spent to retrofit public buildings.

In general, medium-skilled households are the most affected income group. In the simplified version of the total budget, their increase in net wealth is far higher than for the other two income groups, and, in both 'only residential' versions, they are the most indebted ones. Low-skilled households are the least benefitted income group in the simplified version. However, considering that receiving (or taking out) an additional euro has a higher marginal utility for low-skilled households than for the other income groups, when equity-weighting the changes in net wealth, low-skilled households switch position with high-skilled households in the wealth gains. The total utility for the scenario where the operating surplus is distributed to all households is higher than for the scenario where the high-skilled households receive the entire operating surplus. This is an important trade-off in relation to the environmental consequences, in which the scenario concentrating money on high-skilled households presents the lowest GHG emissions, energy consumption and waste production.

With regard to the results comparing the financial balances and the trade effects, both versions of the perturbation present similar results in terms of ratios of lent money in relation to trade balance. Luxembourg, Japan and Ireland appear with the highest ratios, which can be considered as producing potential tensions as they are somehow implicated in the Recovery Plan as financing agents while not benefitting from the trade effects.

Third part

6

Conclusions and perspectives

6.1 Research contributions in a nutshell

As an energy- and carbon-intensive, waste-producing, and resource-intensive sector (labor, natural resources, etc.), the buildings and construction sector plays a key role in helping society achieve the Sustainable Development Goals. Notably, with regard to climate change, the sector is part of the European Union's strategic approaches to achieve carbon neutrality by 2050. In order to attain this ambitious commitment, the sector has been involved in several initiatives worldwide, some examples are "Race to Zero campaign", "Zero Carbon Buildings for All" and the "Science-based target initiative". Particularly in France, the value chain of buildings was included in the list of the priority sectors that are required to present a clear and precise strategy in the form of an emission reduction roadmap by January 2023. This roadmap commits the concerned actors to reduce their emissions gradually until reaching neutrality in 2050. These commitments are examples of actions taken to respond to the environmental pressures exerted by different actors (clients, investors, society, and government), showing a need to act now to reduce the environmental impacts of economic activities in general. This need has led to the development of tools to measure, calculate or estimate the environmental impacts of economic activities, for example, the life cycle assessment methodology (LCA).

In particular for the construction sector, over the last decade, research and policies have shifted the initial focus from reducing the energy consumption of buildings to a broader dimension, including other environmental issues. Examples are circular economy policies in Europe and new policies to reduce the whole life cycle GHG emissions of new buildings, such as the regulations for constructing new buildings based on the whole-life cycle GHG emissions

in Denmark, the Netherlands and France. These policies affect the construction activities, which need to search for less environmentally impacting activities. However, they are focused on taking into account the environmental impacts of one unit of building, and tools to assess large-scale decisions are still lacking.

Considering the absence of a consensual framework for assessing the environmental consequences of large-scale (major) changes occurring in the construction sector, this thesis primary motivation (and first goal) was to answer the research question presented here below as a reminder.

"How to assess the environmental consequences of major changes in the construction sector to help decision-making?"

A literature review was conducted with the purpose of identifying what has been done in other sectors with the matter of assessing the environmental consequences of large-scale changes, including technological change and new policies. Forty articles using CLCA to study policies or non-marginal changes were reviewed. The fields that appeared more frequently in the results are agriculture and biofuels; one possible reason for their particular interest in the consequential approach is to understand the indirect land-use change (ILUC) effects. Overall, the economic models that are more frequently coupled with LCA are the equilibrium models (PE or CGE), agent-based model (ABM), input-output analysis (IOA) and system dynamics, for studying the market-mediated effects, to go beyond the product supply chain and also observe the effects on other economic sectors. This part of the bibliographic research was also focused on answering the second and third research questions of this thesis:

"What are the methodological needs for the application of consequential LCA approaches to the construction sector?"

"How to model the propagation of the effects that are more evident for large-scale decisions?"

According to our findings, the economic models can be very useful for helping to identify the activities in the product system that are expected to change as a consequence of a change in demand for the studied functional unit. Whereas simple models are helpful in identifying major affected markets within the normative system boundaries, more sophisticated economic models are needed to include indirect effects (first and second-order effects). While first-order effects are fairly discussed in the LCA literature, very few studies analyze the second-order effects, such as income redistribution, productivity growth and the relationship between them.

In this thesis, we limited ourselves to the effects of income redistribution, leaving productivity growth to future research. Considering the relevant limitations of computational equilibrium models when it comes to the representation of the financial system, we proposed

the use of SFC models coupled with the IO model to analyze the second-order effects of a change in the economy. SFC models explicitly take into account income redistribution and can provide a consistent accounting framework for describing the effects of an economic shock. At the same time, IO models are appropriate to analyze the relationship between the economy and ecological subsystems through the EE IOTs and are particularly compatible with LCA.

The main contributions of this thesis were, first, to propose an unambiguous framework to assess both first and second-order effects (income distribution effects) and, second, to test it in the case of a new policy concerning the construction sector. The methodology developed here combines the elements from input-output (IO) with stock-flow consistent (SFC) modeling.

SFC models explicitly take into account income redistribution and provide a consistent accounting framework for describing the effects of an economic perturbation. The SFC framework ensures that the monetary balances are indeed consistent as each monetary flow is recorded as an income for someone and an outcome for someone else. Moreover, the SFC framework allows the linkage between the distribution rounds in a consistent way, where the changes in stocks are accounted for as a result of the changes in flows (linking financial and non-financial sides of the economy).

Because the consequential modeling is about how the processes are linked, environmentally extended multi-regional input-output (EE MRIO) tables can be considered as perfectly compatible with consequential LCA, especially if they are built based on the commodity technology construct or by-product technology construct. In the methodology proposed in this thesis, the EE MRIO EXIOBASE was selected because it is publicly available and well-documented, covering a large number of countries and regions and also large number of substance emissions and resource consumption categories.

EXIOBASE provides a large number of flows; however, no information on stocks is provided there. For this reason, one of the contributions of this thesis was to build a "stocks database" consistent with the IO-SFC modeling proposed to obtain monetary redistribution.

Even considering that the dataset selected for obtaining the results presented here was not ideally built according to the desired characteristics for the consequential modeling (which are discussed in chapter 1), the choice for using the monetary IO tables is justified by the fact that they are the most recently available ones and also because, with the monetary IO tables, the trade effects can be compared with the changes in stocks obtained with the stocks database. Ideally, the hybrid version should be converted into a monetary version by multiplying each intermediate output by its basic price so that an equivalent monetary version would be used in the methodology developed in this thesis.

On this matter, a sensitivity analysis was conducted to study how the results vary when using a hybrid version of the IO table. Significant differences were observed in the main contributors to the environmental impacts. The hybrid IO table presents the by-products as

negative inputs and this results in different GHG emissions when the co-production is significant (for example, fly ash in cement).

Therefore, the main result of the thesis is the definition of a framework to assess both first and second-order effects (income distribution effects), presented in Figure 6.1.

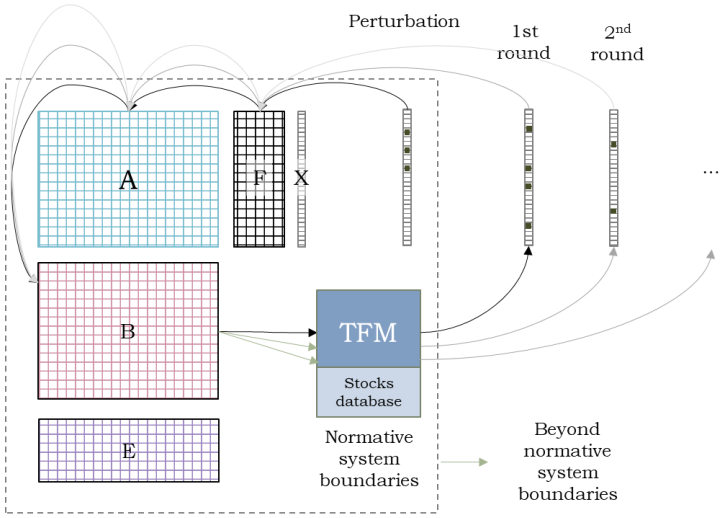


Figure 6.1 | Monetary distribution illustrative representation

Matrix A represents the technological coefficient matrix, with the inputs required per unit of output of each activity. Matrix B and E are the extensions of the IO table, where B presents the coefficients of value-added elements and E shows the coefficients of substance emissions per unit of output. F represents the final demand elements, and X the total outputs, which are equal to total inputs for the monetary version. All of these matrices are obtained from EXIOBASE.

This framework is formalized in a 5-step method, described here below:

- Step 1: Defining the exogenous perturbation
- Step 2: Determining the transactions that are included in the model
- Step 3: Calculating the monetary distribution based on IO models
- Step 4: Accounting the changes in flows in a Transaction-Flow Matrix (TFM)
- Step 5: Calculating the income redistribution

The first step is to define the exogenous perturbation, which must represent the functional unit accordingly to the goals and scope of the study. The second step is determining the transactions that will be part of the study and selecting the pertinent institutional sectors for the study. The third step is to integrate a monetary distribution model, which is coded in Python. The fourth step consists of accounting for the changes in flows in a Transaction-Flow Matrix (TFM) and analyzing the changes in stocks that will affect another round of distribution, called redistribution (step 5).

Technical contributions – environmental consequences of the French Recovery Plan

The second goal of the thesis was to apply the method to a case study in the construction sector. Considering the substantial effect of the Covid 19 pandemic on the economy worldwide, the methodology was applied to the French Recovery Plan, particularly the budget dedicated to fostering and accelerating thermal retrofitting in the national territory. The greatest challenge was to identify how the Recovery Plan directly affected the French economic activities, particularly to quantify how much money households spent on thermal retrofitting products. For that, three versions of the exogenous perturbation were studied.

In the first one, called "total budget, simplified version", the totality of the recovery plan budget was considered as the exogenous perturbation (€5.2 billion), considering both residential and public buildings. In this version, the assumption was that the money from the recovery plan received by households and government actors equals the value spent by them in thermal retrofitting works. A second important assumption was that the activity named "construction works" was the only affected one in the exogenous perturbation, not going further in the analysis on which types of works are favored by the recovery plan.

In the second version, called "only residential, detailed version", the amount of each thermal retrofitting product and equipment was obtained from an econometric model developed for quantifying the thermal retrofitting works induced by financial aids, namely MENFIS (described in Chapter 4); however, only the budget dedicated to residential buildings (€2.0 billion) is considered in this version. According to MENFIS simulations, an increase in financial aid of €2.0 billion increases households expenditure on thermal retrofitting works by €5.8 billion, which was the value of the exogenous perturbation for this second version. This version helps identify the public policy's marginally affected activities, showing an essential gap between the financial aid and the money actually spent by households.

The third version, called "only residential, simplified version" combined elements from the two previous versions. As it is explicit in the name of the version, the scope of the recovery plan is the budget dedicated to residential buildings. For comparison purposes, the value considered in this version is the same as in the second version, i.e., €5.80 billion. The difference from the previous version is that the only activity affected in the exogenous perturbation is "construction works". This version is useful in the case where a simplified estimation of the environmental consequences of an increase in demand for any construction activity, such as thermal retrofitting works.

The environmental consequences assessed were the GHG emissions, energy consumption and waste production. The results are presented in Figure 6.2.

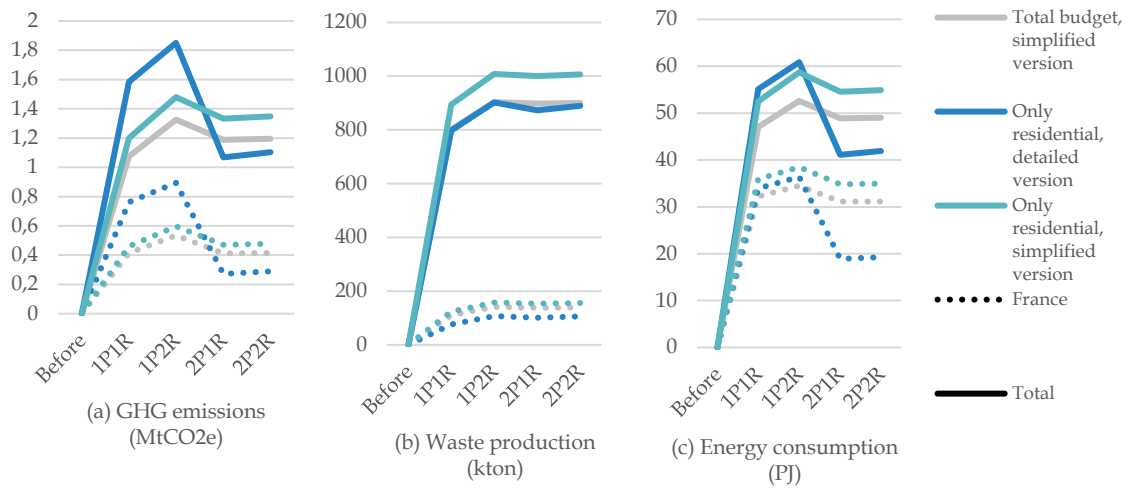


Figure 6.2 | Total results of environmental consequences for the three versions

The results of the three versions present some similarities. The first is that the environmental consequences were more significant in the first round of the first period (1P1R) for the three impact categories, with an induced consumption occurring as a result of the income redistribution (1P2R) also fairly significant. The second point in common is that the consequences occurring in the ROW follow similar patterns for the three versions. Lastly, the third similarity concerns the results of the scenarios proposed for studying the operating surplus distribution to households. For the three versions, the scenario where the operating surplus is paid to each income group following the proportions of the wages and salaries (scenarios 'a') presents the highest environmental impact for the three categories. The lowest impact is observed for the scenario where the operating surplus is saved by households as it does not induce consumption.

The version studying the total budget of the recovery plan (€5.2 billion spent by households and the government to improve the energy efficiency of public and residential buildings) presents the lowest GHG emissions (1.075 $MtCO_2e$, of which 0.413 $MtCO_2e$ occur in France) and energy consumption (47 PJ, of which 32 PJ in France), when compared with the other two versions. The waste production in this version is 802 ktons in the first round of the first period, with very similar patterns as those of the detailed version of residential buildings; though, the latter presents a more significant reduction in waste production in the second period because of a more expressive drop in energy consumption.

For the versions studying the part of the budget dedicated to residential buildings (a total of €5.8 billion of expenditure by households, €2.0 billion coming from the recovery plan, and €3.8 billion coming from their stocks), total GHG emissions were 1.583 $MtCO_2e$ for the detailed version, of which 0.761 tCO_2e occurring in France, and 1.199 $MtCO_2e$ for the simplified version, of which 0.461 $MtCO_2e$ happening in France. These figures represent around 1.01%

for the detailed version and 0.61% for the simplified version of the GHG emissions of the French buildings and construction sector in 2019 (75.1 $MtCO_2e$).

The increase in energy consumption was 55 PJ in the first round of the first period of the detailed version and 52 PJ for the simplified version. The rise in energy use for producing French products and services is 34 PJ for the detailed version and 36 PJ for the simplified version. These numbers represent 1.25% of the total energy consumption of residential and tertiary buildings in France (756 TWh), for the detailed version and 1.32% for the simplified version.

Regarding waste, the additional flows produced due to the recovery plan to improve thermal efficiency in residential buildings are 798 kton for the detailed version and 895 kton for the simplified version. The wastes produced in France are 76 kton in the detailed version and 124 kton in the simplified version, representing 0.18% (detailed version) and 0.29% (simplified version) of total annual contribution of the sector in France (42 Mton).

The induced consumption of goods and services represents from 20% to 23% (simplified versions) and from 15% to 17% (detailed version) of first order GHG emissions. Concerning energy use, the induced consumption represents from 10% to 12% (simplified versions) and from 9% to 10% (detailed version) of first order effects. Finally, concerning waste production, the second order effects represent from 11% to 13% of first order waste production for the three versions. This means that the second-order effects are not negligible and need to be taken into account in new policies.

The relative importance of the increase in emissions in a first period followed by a reduction in a second period was analyzed in relation to the carbon budget defined for buildings in the French Low Carbon National Strategy (LCNS). The target set for the period of 2019 to 2023 is to reduce the French annual average emissions in the period to 422 MtCO2e, of which 78 $MtCO_2e$ are attributed to the buildings sector. The induced consumption of first and second periods affects the whole French economy so that the comparison with the target of any sector included in the LCNS in particular is less relevant. Therefore, the results of GHG emissions of the first round of the first period (1P1R) and the first round of second period (2P1R) presented in Figure 6.2 were adapted to the year-by-year evolution of GHG emissions occurring in France, considering that the recovery plan started to have an effect in 2021.

Considering that the emissions reduction (2P1R) is kept the same from 2022 to 2023, the results for the three versions of the perturbation for the period from 2019 to 2023 are presented in Figure 6.3. It is worth mentioning that the first-order effects are the same for the three scenarios (a,b and c), justifying that only one curve is presented for each version of the perturbation (1, 2 and 3).

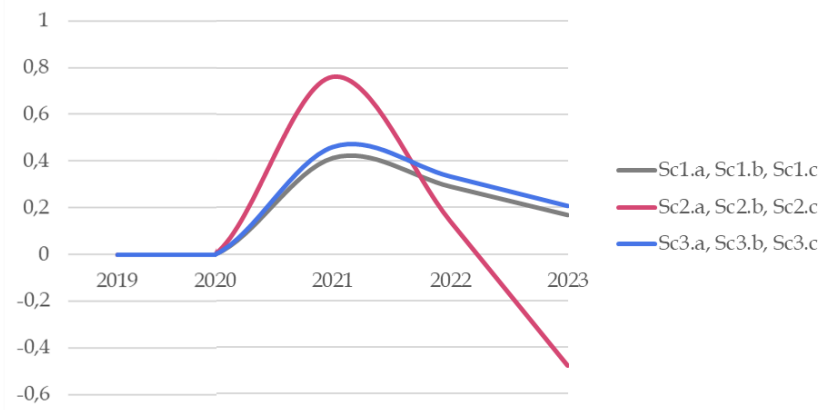


Figure 6.3 | GHG emissions from 2019 to 2023 due to the recovery plan (MtCO2e), only first-order effects

The results presented in Figure 6.3 show that energy consumption reductions do not offset the initial increase for both simplified versions. In contrast, for the detailed version, the saved GHG emissions compensate the initial increase in the first half of 2022.

The environmental consequences occurring in the rest of the world are very significant for the three environmental issues analyzed here, notably for waste production. For the latter, 86% (simplified versions) to 90% (detailed version) of total wastes produced in the first round of the first period are from foreign activities, mainly precious metal ores and concentrates from Asia, America and Africa in both versions. The wastes produced from the induced consumption are also higher in the ROW than in France, however, it drops to around 70% of total waste production for the three versions.

To conclude, the main goal of increasing thermal retrofitting works in France is to reduce energy consumption in the years following the application of a given thermal retrofitting work. The calculations presented in this thesis showed that the time needed to compensate for the extra environmental impacts associated with the increase in thermal retrofitting works varies significantly among the three assessed environmental indicators and between both versions of the perturbation. For the **total budget**, considering only the **French emissions**, the time needed is **3.4 years**, while for the whole **global emissions**, it would be needed **7.8 years** to compensate for the first order emissions and **9.4 years** to compensate for **first and second order emissions**.

For the budget dedicated to **residential buildings, the detailed version**, which is more accurate in terms of marginally affected technologies, shows that **1.2 years** are needed to compensate for **the emissions occurring in France**. When considering the **global perspective**, the time required increases to **2.0 years** and to **2.4 years**, including **the second-order effects**. The s**implified version of the residential buildings** presents the highest time needed to compensate for the increase in emissions. The results show that **3.6 years** are required in order to offset the **French emissions**, **8.2 years** when considering the **global perspective** and **9.9 years** when also including **second-order effects**.

With regard to energy consumption, the time needed is more expressive. When considering the energy use in France, the total budget version shows that **9.5 years** are needed to compensate for the increase in energy use in **France**, rising to **12.7** in a **global perspective** and **14.2 years** when also taking into account **second order effects**. For the detailed version of only residential buildings, the time needed drops to **1.9 year in France**, **2.8 years** from a **global perspective** and **3.1 years** when considering **second-order effects**. For the simplified version, the time needed is **9.8 years** considering **French** energy use, **12.8 years** for the **global** energy use and **14.3 years** when also including **second-order effects**.

Finally, the results for waste production are less favorable since the waste reductions due to energy savings are less significant than those observed for the previous two indicators. The total budget version shows that **41.3 years** are needed to compensate for the increase in waste production **in France**, **144 years** from a **global perspective** and **162 years** when considering **second-order effects**. The reductions in detailed version are less expressive for wastes, where **12 years** are needed **in France**, **28 years** in **total world** and **31 years** when considering **second-order effects**. The simplified version has intermediate values, as the savings in waste production are higher than for the total budget and lower than for the detailed version. The time needed is **33 years** to compensate for the increase in waste production **in France**, **114 years** from **a global perspective and 128 years** also including **second-order effects**.

Technical contributions - socio-economic consequences of the French Recovery Plan

The methodology developed in this thesis allows for assessing a few socio-economic consequences, such as the changes in the net wealth of institutional sectors, the social profile of households affected by the perturbation and also the possible tensions created by investment and trade. The results obtained for the French Recovery Plan showed that the monetary distribution has a positive effect for households, with an increase in net wealth when the whole budget is taken into account and all the expenditure of households is financed by the government. When considering that the money from the Recovery Plan only pays for one part of the thermal retrofitting works, as studied by 'only residential' versions, the total exogenous perturbation is higher than the total budget for thermal retrofitting works and households start the simulations already indebted as they use money from their stock to finance the other part of the thermal retrofitting services.

In general, medium-skilled households are the most affected income group. In the simplified version of the total budget, their increase in net wealth is far higher than for the other two income groups, and, in both 'only residential' versions, they are the most indebted ones. Low-skilled households are the least benefitted income group in all versions. However, considering that receiving an additional euro has a higher marginal utility for low-skilled households than for the other income groups when equity-weighting the changes in net wealth, low-skilled households switch position with high-skilled households in the wealth

gains. The total utility for the scenario where the operating surplus is distributed to all households is higher than for the scenario where the high-skilled households receive the entire operating surplus. This is an important trade-off in relation to the environmental consequences, in which the scenario concentrating money on high-skilled households presents the lowest GHG emissions, energy consumption and waste production.

With the purpose of understanding potential tensions between the lent money and trade benefices, the ratio of lent money from a given country to France divided by the trade balance of the same country as a result of the monetary distribution. Luxembourg, Japan and Ireland have the highest ratios and can present potential tension because they are somehow implicated in the Recovery Plan as financing agents but are not benefited by the trade effects.

6.2 Limitations

The results presented in this thesis have a few limitations that are detailed in the current section. The first one concerns the selected EE-MRIO database used to run the calculations. The monetary IO table from the *pymrio* version is built by using the "industry technology assumption", which assumes that an industry produces its products by using the same technology and splits the outputs in function of their economic value, similar to the economic allocation in LCA. Therefore, it violates one of the desired characteristics of the consequential database, which consists of favoring substitution instead of any partitioning allocation.

The second limitation consists of a lack of validation of the results presented in this thesis. Considering that the French Recovery Plan focuses on the job creation and economic growth, the model presented here allows to identify potential feedback loops that increase the purchasing power of households; however, as the Plan covers other economic activities and we focused only on the thermal retrofitting part, it is challenging to validate the results from what was observed in reality.

Ideally, when conducting an LCA based on IO modeling, it is recommended endogenizing the products that are impacted. This was not done in this thesis because the modeling was performed by using the Exiobase IO tables and extensive data collection was required to model all of the products and equipment that are affected by the increase in thermal retrofitting works.

Additionally, as presented in Chapter 2, a high level of uncertainty is often cited as a major limitation of consequential LCA. This is a recognized limitation, which is often opposed to accuracy, meaning that even if the consequential modeling is more uncertain, it is more representative of the reality. No uncertainty analysis was conducted in this thesis despite the

high importance of the subject. This is pointed out as a limitation of the thesis as it was left out of the scope of the study and room for further work.

To conclude, an important limitation concerns the challenge for decision makers to take into account the second order effects. This thesis presents a framework to take into account these effects, however, we limit ourselves in providing the method, not proposing solutions on how to integrate these features in decision-making.

6.3 Research recommendations

This thesis demonstrates that it is possible to assess second order effects within a transparent and unambiguous framework. However, it opens the windows for further research on the scientific and technical sides. The identified research recommendations are detailed hereafter.

Scientific opportunities

Besides, the links of the social and environmental footprints to the Sustainable Development Goals (SDG) based on EXIOBASE activities are also publicly available since February 2022 (Weidema, 2022). These linkages were also left outside the scope of the current research; however, considering the importance of having a better understanding of the contribution of policies to SDGs, one of the recommendations is to integrate these linkages into the methodology developed here.

The second-order effects evaluated in the proposed methodology left the productivity growth puzzle to further research. The additional money in the stocks of the institutional sectors can be invested on production, contributing to productivity growth. The main issue identified here is a lack of a consensual investment function linking the change in stocks to productivity. This is an opportunity for future research as decisions on how the money is invested may present different environmental and social consequences.

Technical opportunities

In the life cycle assessment step, the contribution of the Recovery Plan to GHG emissions was compared with the French Low Carbon National Strategy targets. This comparison was not easy to do as the construction sector affects different sectors involved in the targets. A common accountability system for the GHG emissions to identify how a given policy will, in fact, contribute to overall reduction in emissions, energy consumption, waste production is thus recommended to help decision making.

One of the identified limitations of this thesis is that we simplified the exogenous perturbation by affecting the products already endogenized. This was done because of a lack

of data for Endogenizing the construction products in the input-output table. Therefore, a recommendation of the current research is to gather data to provide more accurate information on the value-added of a given construction product and also final demand elements (e.g. gross fixed capital formation and specific demands for each construction product divided by income group).

Finally, this thesis focused on three environmental indicators, while other environmental issues significant for the construction sector, which could also be covered by the method, were left for further work. This is the case of land-use change, for example, which has a well-established methodology covered by EXIOBASE and could be very useful in soil artificialisation studies and biodiversity assessments.

7

Développement méthodologique de l'évaluation des conséquences environnementales : application dans le secteur de la construction

7.1 Contexte général de la thèse

Les bâtiments et les activités de construction représentent la plus grande part de la consommation d'énergie, des émissions de gaz à effet de serre (GES) et de la production de déchets comparés aux autres secteurs économiques. Dans une perspective mondiale le secteur est responsable de 36 % de la consommation totale d'énergie finale, de 37 % des émissions totales de CO_2 en 2020 (UNEP, 2011) et de 36 % des déchets totaux en 2015 (UNEP and ISWA, 2015). En Europe, concernant leur contribution à l'épuisement des ressources, les travaux de construction sont responsables de 30 à 50 % de la consommation de matériaux minéraux (argile, sable, gravier, calcaire et pierre de construction), métalliques (fer, aluminium, cuivre) et le bois (Ecorys, 2014). Pour les agrégats (sable, gravier et pierre concassée) ce pourcentage augmente à près de 65 %. De plus, la consommation du secteur est très significative pour quinze parmi les trente matières premières définies comme critiques en 2020 par la Commission Européenne (EC-JRC, 2020). Le niobium (51 % des produits finis européens vont aux éléments de construction), le magnésium (34% des produits finis européens vont aux systèmes de construction), et le borate (59% des produits finis consommés en Europe vont aux produits verriers) sont des exemples pour lesquels le secteur est particulièrement contributeur.

Ces consommations en ressources sont traduites indirectement au travers du produit intérieur brut (PIB). La contribution du secteur au PIB total varie d'un pays à l'autre. Par

exemple, parmi les 56 pays membres de la Commission Economique de l'Organisation des Nations Unies pour l'Europe, la contribution du secteur varie de 1,4 % en Grèce à 10,8 % au Kirghizstan (UNECE, 2021).

On estime que le secteur de la construction fournit 7 % de l'emploi mondial total, soit environ 220 millions de travailleurs dans le monde (ILO, 2019). Les activités du secteur de la construction sont liées à de nombreux autres, tels que les fournisseurs de matières premières (par exemple, les industries métallurgiques et non métallurgiques, le secteur de l'énergie), le transport de matériaux, le traitement des déchets. Ces emplois indirects sont estimés être nettement plus élevés que les emplois directs dans les activités de construction (ILO, 2019).

Les enquêtes menées par la *Royal Institution of Chartered Surveyors* (RICS, 2021), dans le cadre du *World Built Environmental Forum* 2021, ont montré que les principales préoccupations des professionnels du secteur à l'échelle mondiale concernant les questions du développement durable sont : la réduction des déchets, la réduction des émissions de carbone opérationnelles, l'amélioration de la résilience des produits, des matériaux et des composants. L'importance relative de ces questions varie selon les régions, par exemple, au Moyen-Orient et en Afrique, la réduction de la consommation d'eau est très importante, plus de la moitié des participants, alors que ce facteur n'est mentionné que par environ 30 % en Europe. A l'inverse, la réduction des émissions de carbone incorporées est très importante pour les européens, alors que moins de 25 % des répondants du Moyen-Orient et de l'Afrique mentionnent ce facteur comme important.

De plus, selon ces enquêtes, 72 % des répondants ne mesurent pas les émissions des gaz à effet de serre leurs projets. Parmi eux, environ 18 % ont mentionné qu'ils mesureraient les émissions si une approche standardisée existait. Pour ceux qui font cette évaluation, 14 % des participants ont répondu que cela affecte leur choix de matériaux et de composants. Les 86% restant ont répondu que cela n'a pas d'effet sur leurs choix de produits de construction.

Au niveau mondial, la demande des parties prenantes est le facteur moteur le plus fréquemment mentionné par les professionnels du secteur. En Europe, pour plus de 70 % des répondants, la demande des habitants a augmenté de façon modérée (55 %) ou significative (15 %) au cours de l'année précédant l'enquête. Pour les investisseurs, la perception des répondants en Europe est encore plus prononcée, pour plus de 30 % elle a augmenté significativement et pour 45 % elle a augmenté de façon modérée au cours des 12 mois précédant l'enquête.

La demande croissante des habitants et des investisseurs pour des bâtiments durables et les facteurs évoqués plus haut poussant à trouver des solutions soutenables sont des exemples de pressions exercées par différents acteurs du secteur de la construction. Cette pression a conduit le secteur à s'engager dans la transition vers la décarbonation pour 2050. La *Race to Zero*, *Zero Carbon Buildings for All* et la *Science-based target* sont des exemples d'initiatives auxquelles le secteur (par l'intermédiaire d'entreprises, d'agences, etc.) a souscrit.

Récemment, en Europe, certains pays ont lancé de nouvelles politiques visant à réduire les émissions de GES des nouveaux bâtiments sur l'ensemble de leur cycle de vie et des pays comme le Danemark, les Pays-Bas et la France ont approuvé ces nouvelles réglementations. Par exemple au Danemark, le code de construction a introduit un seuil pour tous les nouveaux bâtiments d'une surface supérieure à 1 000 m², qui entrera en vigueur en 2023. La valeur limite initiale du seuil sera réduite progressivement avec un objectif de 5 kg $CO_2e/m^2/an$ fixé à 2030 . Aux Pays-Bas, la performance environnementale du bâtiment (du néerlandais MilieuPrestatie Gebouwen (MPG)) est nécessaire pour accorder des quotas environnementaux aux nouveaux bâtiments résidentiels et tertiaires ayant une surface de plancher supérieure à 100 m², en vigueur depuis 2018. La méthodologie appliquée pour obtenir le MPG d'un bâtiment a été développée au niveau national et est basée sur les principes de l'analyse du cycle de vie (ACV)(Netherlands Government, 2018). La nouvelle réglementation française est détaillée ultérieurement dans le paragraphe 7 .1.1.

Le Royaume-Uni, l'Allemagne et la Suisse ont des exigences en matière d'ACV pour la construction de bâtiments publics. Au Royaume-Uni, le gouvernement a annoncé en 2020 une exigence d'évaluation des GES sur l'ensemble du cycle de vie pour tous les projets et programmes de travaux publics (gouvernement britannique, 2020). En Allemagne, le système d'évaluation de la construction durable (en allemand *Bewertungsystem Nachhaltiges Bauen*) est un outil de planification et d'évaluation des projets de construction publics, basé sur la méthodologie de l'ACV (German Government, 2020). Cet outil est lié à la plateforme allemande de base de données d'information sur la durabilité appelée Ökobaudat, qui contient plus de 1400 déclarations environnementales de produits (DEP) de produits et d'équipements de construction. En Suisse, le label Minergie, créé en 2001 pour fournir des certifications de performance énergétique, inclut depuis 2016 les émissions de GES dans une perspective de cycle de vie (Minergie-ECO) et un niveau minimum est obligatoire pour l'octroi de quotas pour la construction de nouveaux bâtiments publics (Minergie, 2018). Le standard suisse de construction durable (SNBS) couvre d'autres aspects de durabilité que Minergie-ECO et a été mis à jour en 2021 pour être combiné avec ce dernier (Minergie, 2021).

La Finlande, la Suède et la Belgique ont développé des bases de données de DEP pour les émissions de GES du cycle de vie des produits de construction, et les deux pays scandinaves prévoient également de mettre en œuvre de nouvelles réglementations pour respectivement 2025 et 2027 (Toth et al., 2021). Selon le Programme des Nations Unies pour l'Environnement (UNEP, 2021), l'Union européenne disposera probablement dans un avenir proche d'une réglementation commune pour exiger la mesure des émissions de GES sur l'ensemble du cycle de vie des nouveaux bâtiments et imposer des seuils.

Dans une perspective plus large, les États membres des Nations Unies ont adopté en 2015 les 17 objectifs de développement durable (ODD) comme un appel à l'action (voir Figure 7.1). Ces 17 objectifs sont définis dans une liste de 169 cibles, qui sont mesurées et suivies par 231 indicateurs (UNEP, 2015).

Figure 7.1 | Objectifs de développement durable (UNEP, 2015)

Certains des ODD peuvent être facilement associés au secteur de la construction, comme l'eau potable et l'assainissement (ODD6), l'industrie, l'innovation et les infrastructures (ODD9), et les villes et communautés durables (ODD11). Cependant, le secteur peut contribuer à tous les ODD, directement ou indirectement, par ses activités, les effets de ses activités sur la société et la gouvernance des entreprises du secteur. Par exemple, les bâtiments qui sont conçus (ou repensés) pour améliorer la biodiversité, économiser l'eau, les ressources et aider à protéger les forêts, contribuent ainsi à l'ODD 15, plus précisément aux cibles 15.2, 15.5 et 15.9.

La cible 15.2 consiste à promouvoir la mise en œuvre d'une gestion durable de tous les types de forêts, à mettre fin à la déforestation, à restaurer les forêts dégradées et à accroître sensiblement le boisement et le reboisement dans le monde. L'objectif 15.5 consiste à prendre des mesures urgentes et significatives pour réduire la dégradation des habitats naturels, mettre un terme à la perte de biodiversité et, d'ici 2020, protéger et prévenir l'extinction des espèces menacées. Les actions visant à fournir des espaces verts urbains et, plus important encore, à ne pas construire sur des habitats naturels importants pour la préservation de la biodiversité sont cruciales pour atteindre cet objectif. Enfin, l'objectif 15.9 consiste à intégrer les valeurs des écosystèmes et de la biodiversité dans la planification nationale et locale, les processus de développement, les stratégies de réduction de la pauvreté et les comptes, ce qui peut être réalisé par l'intégration de la biodiversité au cœur des plans urbains.

7.1.1 Focus sur la France

La méthodologie développée dans cette thèse est appliquée dans une étude de cas en France, qui est dans une position particulièrement avancée en ce qui concerne les exigences réglementaires en matière d'émissions de GES sur l'ensemble du cycle de vie pour la construction de nouveaux bâtiments (nouvelle réglementation RE 2020 détaillée plus loin dans

ce chapitre). En France, le secteur résidentiel et tertiaire a émis 75,1 $MtCO_2e$ en 2019, soit environ 17 % des émissions nationales totales, et l'ensemble de l'industrie manufacturière (y compris la construction) représentait environ 18 % des émissions totales (Citepa, 2021). Concernant la consommation d'énergie finale, les secteurs résidentiel et tertiaire représentaient environ 46 %, et les industries (y compris la construction) représentaient 19 %. On estime que le secteur du bâtiment et de la construction produit 42 millions de tonnes de déchets par an, entraînant des coûts importants de nettoyage de l'ordre de 340 à 420 millions d'euros (MTE, 2021a). En outre, les activités du secteur représentent 5,6 % du PIB total, 5,5 % du total des employés (INSEE, 2021).

Certaines actions ont été mises en œuvre pour réduire ces chiffres. Depuis 2020, La Stratégie Nationale Bas Carbone (SNBC) (MTES, 2020) a, par exemple, défini des objectifs d'émissions de GES pour la France comme feuille de route pour l'atténuation du changement climatique, déclinant les objectifs nationaux en objectifs sectoriels. Les deux principaux objectifs du SNBC sont d'atteindre la neutralité carbone en 2050 sur le territoire national (émissions ayant lieu en France) et de réduire l'empreinte carbone des Français, y compris les services et les biens de consommation provenant de l'extérieur du territoire français. Ces objectifs impliquent la nécessité d'actions globales et interdisciplinaires, couvrant toutes les activités économiques.

Dans le contexte français des enjeux de durabilité, notamment pour le secteur de la construction, le Centre Scientifique et Technique du Bâtiment (CSTB) aborde de manière systémique les défis socio-économiques de la sécurité, de la santé et du confort, de l'environnement et de l'énergie, pour les bâtiments, les quartiers et les villes. Le CSTB joue de multiples rôles pour soutenir les décideurs des politiques publiques, les constructeurs et les utilisateurs des bâtiments et de l'environnement urbain.

Concernant plus particulièrement les activités de recherche du CSTB, en 2018, le programme de recherche et développement (R&D) à l'horizon 2025 a été lancé, donnant lieu à quatre domaines stratégiques :

- Les bâtiments et les quartiers qui favorisent un habitat harmonieux.
- Les bâtiments et les villes face au changement climatique
- L'innovation et la fiabilité dans la construction et la rénovation
- L'économie circulaire et les ressources pour la construction

Le premier domaine stratégique se concentre sur deux points principaux : concevoir et rénover les bâtiments de manière à ce que le confort, la santé et la sécurité des résidents soient une priorité, tout en développant des quartiers pour un habitat harmonieux. Ce domaine couvre les bâtiments existants et les nouvelles constructions, en tenant compte de leur utilisation future.

Pour les bâtiments et les villes confrontés au changement climatique, l'objectif est double : renforcer l'atténuation et soutenir l'adaptation. Pour l'atténuation, il s'agit de mesurer ou de fournir des outils aux acteurs afin qu'ils puissent mesurer leur impact carbone à court, moyen et long terme. Le domaine de l'adaptation couvre la prévention, la préparation aux événements extrêmes, la protection des personnes et des biens pendant les crises et l'anticipation de la sortie de crise. Ainsi, le CSTB fait le lien entre ceux qui analysent les indicateurs climatiques, ceux qui produisent des données et les concepteurs de bâtiments, en fournissant aux acteurs les éléments (jeux de données, règles de conception) qui leur permettront de concevoir et de rénover dans un contexte de changement climatique.

L'innovation et la fiabilité dans la construction et la rénovation est un domaine stratégique dont l'objectif est de fournir des connaissances pour contrôler la performance des activités de rénovation thermique. Les actions concrètes consistent à améliorer la connaissance du parc bâti, à mesurer l'impact d'une rénovation sur les usages et les usagers, et à anticiper et soutenir les innovations dans les services de rénovation.

Enfin, le domaine de l'économie circulaire s'attache à identifier les flux de matières, à faciliter la valorisation des matières dans le parc bâti existant, et à promouvoir l'intégration de l'économie circulaire dès la conception des produits, des projets de construction et des aménagements territoriaux.

Ces domaines stratégiques de R&D interdépendants sont directement liés aux objectifs de durabilité présentés dans la Figure 7.1. Sachant que, entre autres, le CSTB accompagne les pouvoirs publics sur le développement de nouvelles réglementations en France, la motivation principale pour énoncer cette thèse est de soutenir le positionnement du CSTB auprès des pouvoirs publics sur une base scientifique.

7.1.2 Outils d'évaluation environnementale

Les pressions environnementales exercées par les différents acteurs ont conduit au développement d'outils pour mesurer, calculer ou estimer les impacts environnementaux des activités économiques. En particulier, pour le secteur de la construction, au cours de la dernière décennie, la recherche et les politiques ont déplacé l'objectif initial de réduction de la consommation d'énergie des bâtiments vers une dimension plus large, incluant d'autres questions environnementales.

Afin d'inclure d'autres aspects environnementaux, plusieurs outils sont disponibles, tels que l'évaluation des incidences sur l'environnement (EIE), l'analyse des flux de matériaux (AFM), l'analyse du cycle de vie (ACV), les outils de notation. L'EIE s'agit d'une étude menée pour identifier, décrire et évaluer les impacts environnementaux probables d'un projet proposé, le plus en amont possible. La directive européenne DE 2011/92/UE décrit les principes pour faire l'évaluation des incidences de certains projets publics et privés sur

l'environnement. Selon la directive, l'étude doit inclure les effets directs et indirects sur les êtres humains, la faune et la flore, le sol, l'eau, le climat, le paysage, les biens matériels, le patrimoine culturel et les interrelations entre eux (Directive Européenne 2011/92/UE).

L'AFM est une méthode qui permet d'évaluer l'efficacité de l'utilisation des matériaux en utilisant les informations de la comptabilité des flux de matériaux. Un usage recourant de l'AFM dans le cadre de la construction civile s'inscrit dans des démarches d'étude de faisabilité des projets d'économie circulaire.

L'ACV est définit comme la compilation et évaluation des entrées, des sorties et des impacts environnementaux potentiels d'un système de produits tout au long de son cycle de vie. Il y existe plusieurs approches pour réaliser une étude d'ACV, qui peut prendre en compte une seule catégorie d'impact environnemental (empreinte environnementale) ou plusieurs (ACV complète).

Des outils axés sur une évaluation environnementale particulière sont également disponibles et utilisés par les praticiens de la construction à des fins différentes, comme pour les rapports de l'indice de durabilité Dow Jones, ou le projet de divulgation des émissions de carbone.

Le choix de l'outil à utiliser dépend des objectifs de l'étude ainsi que des questions environnementales couvertes par les outils. Par exemple, les empreintes eau et carbone se concentrent sur un seul impact environnemental sur l'ensemble du cycle de vie d'un produit, d'un projet ou d'un système, tandis que l'ACV peut inclure autant de catégories d'impact que nécessaire.

Les outils de notation sont créés spécifiquement pour les produits ou systèmes concernés. En effet, dans le secteur de la construction, il existe trois principaux outils d'évaluation et de notation de la performance environnementale des bâtiments basés sur des indicateurs semi-quantitatifs : Leadership in Energy and Environmental Design (LEED), la méthode d'évaluation environnementale du Building Research Establishment (BREEAM) et le Comprehensive Assessment System for Built Environment Efficiency (CASBEE)(Kang, 2015).

Dans certains pays, notamment dans l'Union européenne (suite à la directive EIA 2011/92/UE modifiée par 2014/52/UE), une EIE peut être légalement requise avant la délivrance d'un permis de construire. Les informations qui doivent être fournies peuvent concerner les ressources employées pour réaliser les travaux de construction ainsi que l'élimination des déchets pendant la phase de construction, la durée des travaux de construction, y compris les informations sur le bruit, la poussière, les odeurs et les émissions lumineuses prévues pendant la phase de construction (European Commission, 2014).

Une analyse approfondie de ces outils dépasse le cadre de cette thèse, puisque l'accent est mis ici sur l'ACV. Cette dernière est une approche couramment utilisée pour évaluer les émissions de GES sur l'ensemble du cycle de vie des bâtiments neufs, comme présenté dans la section précédente, et est beaucoup plus détaillée que les outils de notation et l'EIE. En outre,

l'ACV évite de déplacer les questions entre les différentes étapes du cycle de vie, et entre les questions environnementales.

7.1.3 Analyse du cycle de vie : la diversité d'approches

L'analyse du cycle de vie (ACV) est une méthodologie permettant de quantifier les impacts environnementaux d'un produit ou d'un service à toutes les étapes de son cycle de vie, depuis l'extraction des matières premières jusqu'au traitement en fin de vie. Les principes et les exigences majeurs pour la réalisation d'une ACV sont définis par les normes ISO 14040-44 (ISO, 2006c, 2006b). Ce cadre méthodologique repose sur les quatre étapes suivantes : (1) définition de l'objectif et du champ de l'étude, (2) analyse de l'inventaire, (3) évaluation de l'impact et (4) interprétation, comme le montre la Figure 7.2.

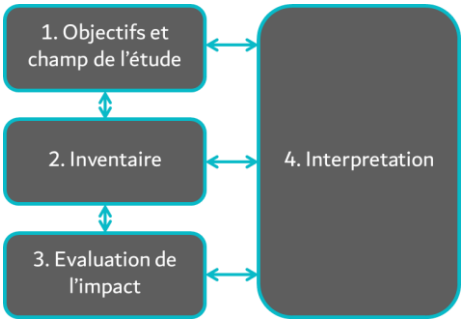


Figure 7.2 | Phases d'une étude d'ACV (Source : Norme ISO14040:2006)

Des exemples de l'application de l'ACV dans le secteur de la construction sont les normes européennes existantes spécifiques aux produits de construction (EN 15804+A2 (CEN, 2019)) et aux bâtiments neufs et existants (EN 15978:2012 (CEN, 2012b)), qui sont utilisées par les producteurs de produits de construction pour déclarer leur profil environnemental et par les entrepreneurs du bâtiment pour identifier les opportunités potentielles d'éco-conception. En ce qui concerne les systèmes à une échelle plus importante, l'ACV a été utilisée pour fournir une évaluation environnementale de quartiers et d'îlots urbains (Lotteau et al., 2015), mais aussi de quartiers entiers (Mailhac et al., 2016).

Les normes européennes mentionnées sont basées sur une approche attributionnelle, qui est également l'approche la plus fréquemment appliquée par les praticiens de l'ACV à ce jour bien qu'il existe une variété d'approches de modélisation de systèmes d'ACV (voir Figure 7.3), chacune ayant un objectif défini et orientée pour répondre à une question spécifique (pour une revue approfondie, voir (Guinée et al., 2018)).

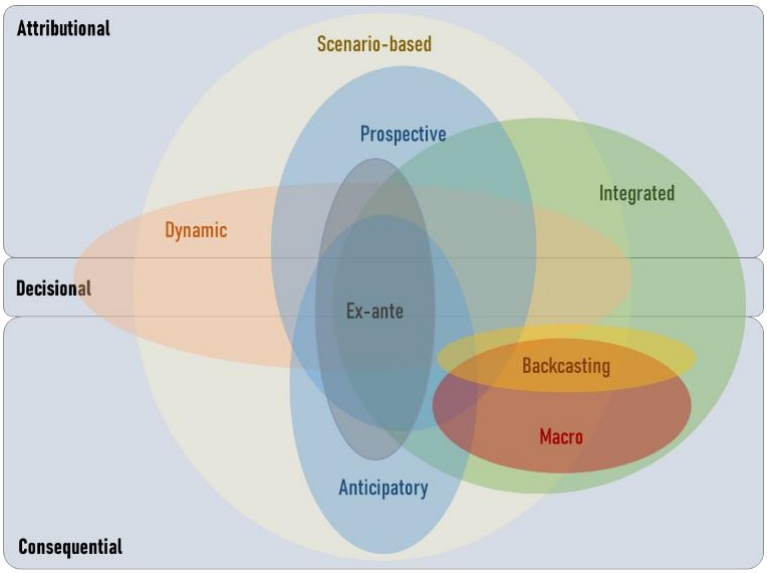


Figure 7.3 | Combinaisons théoriques possibles des différentes approches (Source : analyse théorique de l'auteur)

Les trois approches représentées horizontalement dans la Figure 7.3 sont les approches conséquentielle, attributionnelle et décisionnelle. Elles diffèrent les unes des autres par des points méthodologiques clés, définissant la structure de l'étude et peuvent être combinées de manière cohérente avec d'autres approches, à l'exception des approches macro et backcasting, qui sont des types particuliers de l'analyse du cycle de vie conséquentielle (ACV-C).

L'approche décisionnelle n'est pas aussi fréquemment utilisée que les approches attributionnelles et conséquentielle. Une recherche sur Scopus a été effectuée en janvier 2022 avec le mot clé « decisional LCA » et seuls 18 articles sont apparus dans les résultats. En remplaçant ce mot clé par « consequential» ou « attributional », les résultats augmentent alors significativement, passant de 18 articles à environ 450 et 500 documents, respectivement. Or toutes les recherches concernant l'ACV attributionnelle ne sont pas implicitement mentionnées comme telle, en effet celle-ci étant l'approche de modélisation la plus conventionnelle.

Les approches les plus connues sont donc l'attributionnelle (ACV-A) et conséquentielle (ACV-C). Des différences observées pour ces deux approches sont illustrées dans la figure suivante.

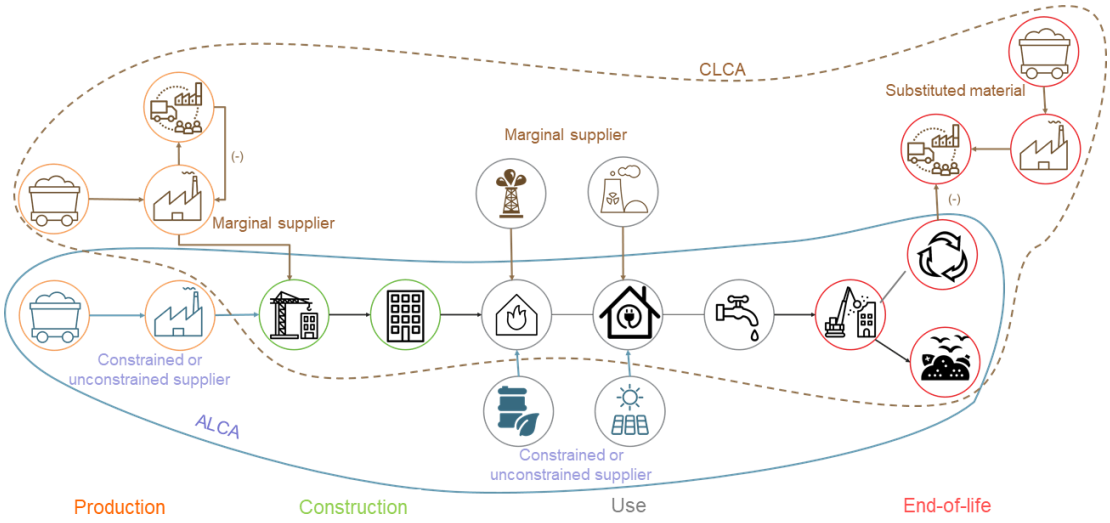


Figure 7.4 | Différences méthodologiques entre ACV-A et ACV-C (Source : analyse de l'auteur)

La première différence révèle la manière dont elles traitent les processus multifonctionnels. L'ACV-C utilise la méthode de substitution comme procédure pour éliminer les sous-produits dans un procédé, où ils sont plutôt considérés comme des intrants négatifs. Il s'agit alors de prendre en compte une contrainte de la demande, réduisant la demande pour la production alternative du coproduit (Schaubroeck et al., 2021). L'ACV-A utilise la méthode d'allocation (ou de partitionnement) pour le fractionnement des processus en fonction d'un critère défini (masse, contenu énergétique, valeur économique, etc.). L'expansion de système, communément confondue avec la substitution dans la littérature, traite des processus multifonctionnels en considérant toutes les fonctionnalités du système étendu. Il est assez discuté dans la littérature que les deux approches sont capables d'utiliser l'expansion de système (Majeau-Bettez et al., 2018; Schaubroeck et al., 2021; Schrijvers et al., 2020) (Majeau-Bettez et al., 2018 ; Schaubroeck et al., 2021 ; Schrijvers et al., 2020).

La deuxième différence concerne le fournisseur (processus) marginal par rapport au fournisseur moyen. Marginal, en économie, signifie une unité supplémentaire, par exemple, le produit marginal signifie la quantité supplémentaire de production que les entreprises obtiennent à partir d'une unité supplémentaire d'un intrant défini (Mankiw, 2009). Dans le contexte de l'ACV, les processus marginaux sont ceux qui réagissent au changement étudié de la demande, et pas nécessairement les processus normatifs liés (Brandão et al., 2017).

Récemment, Schaubroeck et al. (2021) ont étudié les différentes interprétations du système de produits dans la norme ISO 14040-44 et dans le guide du Programme des Nations Unies pour l'environnement (PNUE ou UNEP en anglais) pour l'ACV (UNEP, 2011). Selon cette norme, un système de produit étudié en ACV-C coïncide avec le cycle de vie du produit, c'est-à-dire qu'il inclut les processus normatifs liés au cycle de vie d'un produit. En revanche, pour le PNUE, les « systèmes analysés dans ces ACV sont constitués uniquement des processus qui sont effectivement affectés par la décision, c'est-à-dire qui modifient leur production en raison d'un signal qu'ils reçoivent d'une chaîne de cause à effet dont l'origine

est une décision particulière », signifiant que les processus interconnectés de certaines phases du cycle de vie (ou de toutes) peuvent être laissés en dehors des limites du système s'ils ne sont pas censés changer à cause de la décision.

Par exemple, pour la norme ISO 14040-44, le système de produits considère que la décision d'acheter une nouvelle maison étant déjà construite avant la prise de décision comprend toutes les phases du cycle de vie d'une maison (extraction des matières premières, transport, production, utilisation et fin de vie). D'autre part, selon le PNUE (2011), le système de produit prend en compte l'utilisation de la maison et les réponses du marché pour produire d'autres maisons qui sont liées à cette décision (et les étapes respectives du cycle de vie).

Considérant que la norme ISO 14040-44 ne présente pas une définition claire des approches conséquentielle et attributionnelle, Schaubroeck et al. (2021) ont récemment passé en revue les définitions données dans la littérature en suivant quatre critères : la logique (pas de contradictions), le nom (lien avec le concept), le consensus (le concept est soutenu par une large communauté) et l'application. Les auteurs ont alors retenu deux définitions respectant ces quatre critères : celle du manuel « International Life Cycle Data System (ILCD) » (EC-JRC, 2010) et celle proposée dans le guide « Global Guidance Principles for LCA Databases » du PNUE (UNEP, 2011), toutes deux présentées dans le Tableau 7.1.

Tableau 7.1 | Définitions d'ACV-C

Source	Définition
(UNEP, 2011)	*Approche de modélisation du système dans laquelle les activités d'un système de produits sont liées de sorte que les activités sont incluses dans le système de produits dans la mesure où l'on s'attend à ce qu'elles changent à la suite d'une modification de la demande d'unité fonctionnelle*
(EC-JRC, 2010)	*Approche visant à identifier les conséquences qu'une décision prise dans le système de premier plan a sur d'autres processus et systèmes de l'économie, tant dans le système d'arrière-plan du système analysé que sur d'autres systèmes. Il modélise le système analysé en fonction de ces conséquences. Le modèle de cycle de vie conséquentiel ne reflète donc pas la chaîne d'approvisionnement spécifique ou moyenne réelle (ou prévue), mais une chaîne d'approvisionnement générique hypothétique est modélisée et pronostiquée selon les mécanismes du marché, et incluant potentiellement des interactions politiques et des changements de comportement des consommateurs*

Pour cette thèse, la définition de l'UNEP (2011) a été retenue comme étant la plus générique et appropriée, du fait que le UNEP est une institution mondiale et que, par conséquent, le critère de consensus atteint une communauté plus large. En plus, la différence entre ces deux définitions n'est pas significative. La définition de l'UNEP, à la fois plus générique, se base sur l'idée d'une modification de la demande de l'unité fonctionnelle, qui peut être plus précis pour la mise en place d'un modèle économique.

En outre, en ce qui concerne les définitions et les concepts, les auteurs ont constaté qu'il existe encore des idées erronées sur la signification de l'ACV-C. Ils ont donc identifié quelques

études récentes considérant à tort que l'approche conséquentielle n'est théoriquement appropriée que pour étudier les changements à grande échelle, comme l'indique le manuel de l'International Life Cycle Data System (ILCD) (EC-JRC, 2010). Pour les auteurs, la stratégie du choix d'une approche est liée aux objectifs de l'étude et non à l'ampleur du changement.

7.1.4 Analyse du cycle de vie conséquentielle appliquée au secteur de la construction : la revue bibliographique

Dans le cadre de cette thèse, une recherche bibliographique a été faite pour identifier les documents de recherche (articles, communications de conférences, rapports, manuscrits de thèse, etc.) utilisant l'approche conséquentielle pour répondre à des questions inscrites dans le domaine de la construction et du bâtiment. Quarante-trois études ont alors été sélectionnées pour être examinées en fonction des critères suivants :

- Objectif
- Echelle et horizon temporel
- Combinaison avec d'autres approches ACV
- Méthode d'identification des fournisseurs concernés
- Effets de rebond
- Méthodes d'ACV
- Incertitude et analyse de sensibilité

Globalement, la justification du choix d'une approche conséquentielle est associée à quatre raisons différentes : fournir des informations systémiques pour la prise de décision, étendre les limites du système et inclure également les effets de substitution (ce qui est l'une des différences méthodologiques entre les approches attributionnelles et conséquentielles), inclure les effets indirects et/ou internaliser les externalités environnementales.

Les auteurs qui mentionnent la pertinence de l'approche conséquentielle pour l'aide à la prise de décision citent les exemples de décisions suivants : l'élaboration de politiques, la possibilité de substitution d'un produit ou d'un système de construction, la comparaison d'alternatives de construction circulaire, la construction ou la rénovation d'un bâtiment, la possibilité d'achat d'un produit de construction et la décision de l'utilisation future de friches industrielles récupérées.

Dans l'ensemble, la moitié des études examinées comparent les résultats des approches attributives et conséquentes. La majorité des auteurs obtiennent des différences significatives dans les résultats, principalement justifiées par la façon dont les approches traitent les fournisseurs affectés (les fournisseurs marginaux sont plus impactant) et les émissions évitées (à partir des effets de substitution dans l'approche ACV-C).

Contrairement à ce que l'on pourrait attendre des lignes directrices de l'ILCD, la grande majorité des études évaluent un changement à petite échelle (marginal), prouvant la

pertinence de l'ACV-C indépendamment de l'échelle du changement. Seules deux études examinées peuvent être considérées comme évaluant un changement à grande échelle. L'une d'entre elles a utilisé un modèle d'équilibre partiel pour identifier les marchés affectés, tandis que l'autre a utilisé des études de marché et de la littérature à cette fin. Il a été constaté qu'il est courant de mentionner l'horizon temporel dans les études, les conséquences à long terme étant les plus fréquentes car ce sont les effets les plus dominants.

Les méthodes d'identification des fournisseurs concernés, qui constituent le principal défi de l'analyse comparative entre les entreprises, varient d'une étude à l'autre. La plus fréquente est la procédure par étapes de Weidema (2003, 2009), suivie des méthodes basées sur le commerce, des modèles d'équilibre et des avis d'experts. Les méthodes basées sur le commerce semblent être actuellement pertinentes dans la littérature et peuvent aider le secteur de la construction à identifier les fournisseurs potentiels pour les matières premières demandées. La combinaison de ces méthodes basées sur le commerce avec une modélisation économique cohérente constitue également une opportunité pour le secteur de la construction.

Cet examen a révélé que les effets de rebond ont rarement été étudiés par le secteur de la construction dans le cadre des études d'ACV-C. Bien que cela ait été mentionné comme une limitation et une recommandation pour des travaux futurs dans les articles les plus récents. Les effets de second ordre de Sandén et Karlstrom (2007) ont été évalués par quatre études lorsque l'augmentation de la demande oblige l'offre à s'adapter et à répondre à la demande. Enfin, les effets transformationnels de Greening et al. (2000) ont été évalués par un modèle d'équilibre partiel dans une étude. L'intégration des effets de rebond reste très rare et semble être une opportunité pour des développements futurs, car elle peut avoir une forte influence sur les résultats des études.

L'utilisation d'indicateurs intermédiaires reste la plus courante parmi les études examinées. Les exemples d'utilisation d'indicateurs à score unique et d'indicateurs de point final sont moins courants mais représentent 10 des 43 études. Aucune catégorie d'impact ou indicateur particulier n'a été mentionné comme étant pertinent. Les indicateurs les plus courants parmi les études examinées sont le réchauffement climatique et l'épuisement abiotique.

L'incertitude de l'approche conséquentielle est considérée comme l'une de ses principales limites, or la plupart des études ne réalisent pas d'analyse d'incertitude. Les études qui l'incluent utilisent l'une des méthodes suivantes : Analyse de Monte Carlo, modélisation de scénarios, incertitudes des ensembles de données et analyse de sensibilité. D'autre part, la majorité des études examinées ont effectué une analyse de sensibilité, même si la raison principale n'est pas d'évaluer l'incertitude des études, elle semble améliorer la robustesse des résultats de l'ACV-C.

Même si elle est considérée comme pertinente pour l'élaboration des politiques, seule une étude de cas a appliqué l'approche conséquentielle dans une politique publique. En outre,

il semble consensuel que l'approche conséquentielle soit également pertinente pour inclure les effets de rebond et seules sept études les ont inclus dans leurs évaluations.

7.2 Problématique du travail de thèse

Le secteur du bâtiment et de la construction fait partie des approches stratégiques visant à atteindre la neutralité carbone en 2050. En outre, le secteur (par le biais d'entreprises, d'institutions et d'associations) s'est engagé dans des initiatives spécifiques et a signé des accords dans le monde entier pour réduire les émissions, les déchets et la consommation énergétique des bâtiments. Le secteur a également le sentiment que les parties prenantes (clients, consommateurs, investisseurs, gouvernements, etc.) exigent de plus en plus des actions concrètes pour que les engagements et les accords aient un effet réel. Cela signifie alors que les actions qui sont actuellement appliquées à une unité de produit de construction, une unité d'équipement ou une unité de bâtiment devront être appliquées à des extensions plus importantes (décisions à grande échelle).

Cependant, pour l'instant, les outils utilisés par le secteur du bâtiment et de la construction pour évaluer les avantages environnementaux des actions proposées sont principalement appliqués pour des décisions à petite échelle (unités de produit de construction, unités d'équipement et unités de bâtiment). Une question technique semble donc évidente : « Ces avantages dans les décisions à petite échelle sont-ils encore bénéfiques pour l'environnement lorsqu'ils sont propagés dans des extensions plus importantes, où les effets indirects pourraient être significatifs ? » et par conséquent « Si et dans quelle mesure ces actions contribuent aux objectifs de développement durable ? ».

Pour cette thèse, l'hypothèse privilégiée est qu'une approche conséquentielle reste plus appropriée pour aider à répondre à ces questions puisque la mise en échelle d'applications inférieures à des applications supérieures peut présenter des relations de cause à effet qui vont au-delà de la chaîne d'approvisionnement du produit, et plus encore, au-delà des frontières normatives du système.

Dans ce but, en considérant la différence entre les concepts d'ACV-A et d'ACV-C, et conscient que l'ACV-C n'est seulement appropriée aux décisions à grande échelle (Schaubroeck et al., 2021), **l'objectif principal de cette thèse est donc de proposer un cadre méthodologique pour la réalisation d'une ACV-C appliquée aux décisions à grande échelle dans le secteur de la construction.**

Questions de recherche

Compte tenu du contexte présenté ci-dessus, et principalement en l'absence d'un cadre consensuel pour évaluer les conséquences environnementales des changements à grande échelle (majeurs) survenant dans le secteur de la construction, la question de recherche centrale proposée est la suivante :

Encadré 1

QR1 : Comment évaluer les conséquences environnementales des changements majeurs dans le secteur de la construction pour aider à la prise de décision ?

Ce questionnement appel d'autres questions complémentaires auxquelles ce travail de thèse cherchera à répondre également, qui sont :

QR2 : Quels sont les besoins méthodologiques pour l'application des approches ACV conséquentes au secteur de la construction ?

QR3 : Comment modéliser la propagation des effets aux petites échelles, ceux-ci étant plus évidents pour les décisions à grande échelle ?

7.3 Théories et méthodes - Contexte

Une étude bibliographique concernant l'application de l'ACV-C à changements de large échelle a été réalisé, comme par exemple l'usage de l'ACV-C dans les politiques publiques et pour évaluer les changements technologiques à large échelle. Dans ce cadre, 40 articles ont été retenus pour la revue se basant sur les quatre critères suivants : la justification du choix de l'approche conséquentielle, le modèle économique utilisé (cas échéant), la prise en compte des effets rebond, et l'analyse d'incertitude.

Les domaines qui apparaissent le plus fréquemment dans les résultats sont l'agriculture et les biocarburants. Une raison possible de leur intérêt particulier pour l'approche conséquentielle est de comprendre les effets indirects du changement d'affectation des terres. En accord avec cette hypothèse, la majorité des études justifient le choix d'utiliser une approche conséquentielle pour évaluer les impacts directs et indirects, cette dernière signifiant « d'aller au-delà des activités de la chaîne d'approvisionnement » ou « d'effets sur les autres secteurs » ou encore d'« effets induits ».

Plus de la moitié des articles ne mentionnent pas les effets de rebond dans leurs études, seul un cinquième les inclut explicitement dans leurs évaluations. Les effets médiés par le marché, plus précisément les effets des prix sur l'offre et la demande, sont les plus cités par les auteurs. Deux études ont évalué les effets rebonds de substitution, évalués par l'élasticité de l'offre des substituts, pouvant être directement obtenue à partir du modèle d'équilibre utilisé dans les deux études.

Enfin, le plus récurrent est de ne pas inclure une analyse approfondie des incertitudes. Malgré tout, trois projets ont étudié les incertitudes au moyen de simulations de Monte Carlo et deux ont utilisé une analyse de sensibilité, dont une analyse de sensibilité globale.

Les modèles les plus fréquemment couplés à l'ACV-C dans la littérature, selon notre revue et les revues précédentes, sont les **modèles d'équilibre (partiel ou général)**, suivis par la **modélisation basée sur les agents (MBA), l'analyse d'entrées-sorties (AES).**

Pour cela, une analyse plus détaillée de ces quatre modèles a été réalisé, ce qui permettra de répondre aux questions de recherche 2 et 3, présentées pour mémoire dans l'encadré 2.

Encadré 2

QR2 : Quels sont les besoins méthodologiques pour l'application des approches d'ACV conséquentielle au secteur de la construction ?

La QR2 s'intéresse à l'identification des besoins méthodologiques pour l'application d'une approche conséquentielle, c'est-à-dire les besoins méthodologiques pour identifier les activités qui « sont censées changer en conséquence d'un changement dans la demande d'unité fonctionnelle », selon la définition du PNUE (UNEP, 2011).

QR3 : Comment modéliser la propagation des effets qui sont plus évidents pour les décisions à grande échelle ?

La QR3 est axée sur la propagation des effets, également appelés effets de rebond. Par conséquent, il convient d'analyser la capacité des modèles économiques examinés à identifier et à propager les activités qui changent en fonction d'une unité supplémentaire de l'unité fonctionnelle, et dans quelle mesure (ou à quel degré, ou dans quel ordre).

L'effet de rebond est un terme large et doit être défini pour être clarifié. Dans cette thèse, nous distinguons deux niveaux d'effets rebonds, les **effets de premier ordre** des **effets de second ordre** comme suit.

- Le terme **« effets de premier ordre »** correspond aux activités qui se produisent à la suite d'une dépense spécifique (décision de consommation) jusqu'à ce qu'il y ait une suite de ces activités sous forme de paiements aux facteurs primaires (salaires, impôts sur la production, revenus d'entreprise et loyers). Cela inclut les activités qui se produisent en tant qu'effets de rebond des différences de prix à la consommation puisque ces activités se produisent également à la suite d'une décision de consommation spécifique.
- Le terme **« effets de second ordre »** est alors défini comme les effets d'une décision de dépense spécifique sur la redistribution des revenus, les habitudes de consommation et la croissance de la productivité. Ces effets se produisent après que la dépense initiale a été reçue par les agents de facteurs primaires (travailleurs, gouvernement ou bénéficiaires de redistributions fiscales, entrepreneurs ou rentiers), c'est-à-dire à la suite d'une nouvelle dépense de la dépense initiale dans des boucles de dépenses ultérieures.

La redistribution des revenus est le mécanisme qui décrit comment l'argent reçu par les agents des facteurs primaires est finalement redistribué entre les agents impliqués dans tous les secteurs économiques et toutes les classes de revenus. Pour comprendre ce mécanisme, des informations sur l'épargne, les investissements et les bénéfices sont nécessaires. En outre, comme la productivité est affectée par les investissements, la redistribution des revenus a un effet important sur la croissance de la productivité, ainsi que sur les paramètres et les équations qui sont utilisés pour quantifier le comportement des consommateurs, tels que les propensions à épargner et à consommer, les habitudes de consommation et les fonctions de consommation et de production.

La croissance de la productivité apparait lorsque l'innovation a lieu au sein d'une entreprise (phénomènes microéconomiques) et, lorsque l'innovation est adoptée par d'autres entreprises et a des conséquences sur d'autres activités économiques (conséquences macroéconomiques). On trouve dans la littérature de nombreux modèles économiques sophistiqués étudiant ces effets, issus de différentes écoles économiques (néoclassiques à hétérodoxes) (pour des revues, voir Blecker et Stefford, 2019 et Kemp-Benedict, 2017).

7.3.1 Revue bibiliografique sur les modèles couplés à l'ACV-C

Compte tenu des enjeux présentés ci-dessus, les modèles d'équilibre partiel (MEP) et général (MEG), le modèle basé sur les agents (MBA), l'analyse d'entrées-sorties (AES), identifiés dans la revue bibliographique précédente, et les modèles stock-flux cohérents (SFC) ont été étudiés sur les critères suivants :

- Niveau de transparence
- Collecte de données
- Capacité à inclure les effets de rebond (premier et second ordre)
- Capacité à inclure les flux commerciaux
- Capacité à inclure les flux financiers

Le niveau de transparence est important pour comprendre les mécanismes qui sous-tendent le modèle et les équations représentant l'hypothèse du modèle. Un haut niveau de transparence permet de justifier les résultats et également d'appliquer ou de proposer des améliorations pour une meilleure représentation du système étudié.

La collecte de données est un critère décisif dans le choix d'une méthode. En effet, pour la modélisation cette collecte peut prendre beaucoup de temps et constituer l'un des principaux défis de la recherche. D'autres questions liées à l'existence de bases de données pouvant être utilisées par les modèles sont également importantes, comme des mises à jour régulières, un niveau de représentation des technologies, la désagrégation des données. Ces autres critères étant davantage liés à la base de données qu'à la méthode, ils ont été laissés en dehors du champ d'étude pour cette thèse.

La capacité du modèle à inclure les effets de rebond est étudiée principalement en raison de la question de recherche QR3. Dans un monde globalisé, les activités économiques sont liées entre elles au-delà des frontières territoriales et le déplacement des impacts est l'un des problèmes souvent identifiés dans les recherches précédentes. Pour ces raisons, la façon dont le modèle traite les flux commerciaux est analysée comme un critère.

Enfin, nous vivons dans une économie hautement financiarisée et extrêmement interconnectée. Le capital financier n'est pas limité par des frontières physiques et tout changement politique ou technologique a un rôle sur la question des changements dans les stocks (bilans). Ce critère a donc été inclus pour comprendre la capacité du modèle à capturer le côté financier de l'économie.

Le résultat de cette revue orientée aux modèles est présenté dans le Tableau 7.2.

Tableau 7.2 | Comparaison des modèles examinés sur la base de cinq critères (Source : analyse bibliographique de l'auteur)

Critère	**Modèles d'équilibre**		**Modèles basés sur les agents**	**Analyse d'entrées-sorties**	**Modèles stock-flux cohérents**
	Partiel	Général			
Niveau de transparence	Elevé	Bas	Elevé	Elevé	Elevé
Collecte de données	Plusieurs bases de données sont disponibles	Plusieurs bases de données sont disponibles	Complexité dans la collecte des données, en fonction du niveau de désagrégation des agents	Plusieurs bases de données sont disponibles	De multiples bases de données sont nécessaires, provenant de différentes sources, rendant la collecte d'informations relativement complexe
Capacité à inclure les effets de rebond	Inclusion des effets de premier et de second ordre, mais seulement partiellement car il ne couvre qu'une partie de l'économie.	Possibilité d'inclure les effets de premier et de second ordre	Possibilité d'inclure les effets de premier et de second ordre	Normalement, seuls les effets de premier ordre	Possibilité d'inclure les effets de premier et de second ordre
Capacité à inclure les flux commerciaux	Partiellement inclus	Inclus	Uniquement lorsqu'ils sont associés à un modèle économique	Inclus dans le tableau d'entrée-sortie (TES) multirégional	Peut être inclus lorsqu'il est nécessaire de le modéliser
Capacité à inclure les flux financiers	Souvent négligé, ou trop simplifiés	Souvent négligé, ou trop simplifiés	Uniquement lorsqu'ils sont associés à un modèle économique	Non capturé	Bonne représentation de l'aspect financier de l'économie

7.3.2 Pourquoi utiliser un modèle économique, et quel modèle choisir ?

En reprenant les questions de recherche qui ont motivé ce chapitre, le premier objectif était d'identifier les besoins méthodologiques pour l'application de l'ACV-C au secteur de la construction. Le second objectif était d'identifier les méthodes utilisées pour propager les effets qui sont plus évidents pour les décisions à grande échelle.

La revue de la littérature sur l'utilisation de l'ACV-C comme méthode d'évaluation des décisions ou des politiques à grande échelle a montré que les modèles économiques peuvent être très utiles pour aider à identifier les activités du système de produits qui sont censées changer en conséquence d'un changement de la demande d'unité fonctionnelle. Les modèles simples, tels que présentés par Weidema et al., 2009, peuvent être très utiles pour identifier les principaux marchés affectés, cependant, lorsque d'autres effets indirects, les effets de rebond médiés par le marché tels que définis par Plevin (2017), un modèle économique basé sur une base de données multirégionale est nécessaire.

Les effets de premier ordre sont assez bien décrits dans la littérature, par exemple, l'utilisation d'approches orientées vers le consommateur comme l'application des courbes d'Engel (Font Vivanco et al., 2015), les propensions marginales à dépenser (Alfredsson, 2004), les changements de revenu marginal affectant les modèles de consommation (Thiesen et al., 2008) ou l'utilisation d'approches orientées vers l'industrie, comme l'utilisation du coût marginal de production (Kätelhön et al., 2015).

Dans le domaine des évaluations environnementales, en particulier dans les analyses de cycle de vie, comme décrit dans les sections précédentes, la croissance de la productivité a été étudiée en intégrant des modèles basés sur les agents et des courbes d'apprentissage ou des relations de loi de puissance. En outre, nous avons également trouvé des exemples d'inclusion des effets de redistribution des revenus en utilisant des modèles d'équilibre calculable, qui sont également capables de prendre en compte les effets de la croissance de la productivité.

Les courbes d'apprentissage et les relations de type loi de puissance montrent comment l'expérience de production cumulative et les coûts moyens sont associés, ce qui permet de prendre en compte l'échelle (Argote & Epple, 1990 ; Bergesen & Suh, 2016). S'agissant d'outils simples et intuitifs, ils ne sont pas intrinsèquement associés aux investissements et autres relations monétaires entre différents secteurs économiques, mais ils pourraient être intégrés dans les modèles économiques. Des exemples d'utilisation des courbes d'apprentissage pour évaluer la croissance de la productivité peuvent être trouvés dans Bergesen et Suh (2016) et Sandén et Karlström (2007).

Les modèles d'équilibre général ou partiel sont en mesure de couvrir la croissance de la productivité à travers les équations d'équilibre des prix indexant chaque entreprise par sa productivité, en considérant le taux de croissance (attendu) respectif.

La redistribution des revenus peut être évaluée par les modèles d'équilibre partiel ou général à travers les effets multiplicateurs, résultant de la perturbation du flux circulaire des revenus au sein de l'économie par l'injection de dépenses supplémentaires. Les effets multiplicateurs sont obtenus à partir des liens de production et de consommation de la matrice de comptabilité sociale (MCS), également connus sous le nom de multiplicateurs de la MCS, qui retracent les effets des changements de la demande à travers les changements de la production, du revenu des ménages, puis de la demande finale (Breisinger et al., 2009 ; Robinson, 2006 ; Thorbecke, 2000).

Même s'il est étroitement lié, l'effet de redistribution des revenus peut être analysé séparément de son influence éventuelle sur la croissance de la productivité. Dans cette thèse, nous nous limiterons aux effets de la redistribution des revenus et laisserons le puzzle de la productivité (croissance) aux recherches futures. Compte tenu des limites pertinentes des modèles SFC en ce qui concerne la représentation du système financier, nous proposons l'utilisation de modèles SFC couplés aux modèles d'analyse d'entrées-sorties pour analyser les effets de second ordre d'un changement dans l'économie. Les modèles SFC prennent explicitement en compte la redistribution des revenus et peuvent fournir un cadre comptable cohérent pour décrire les effets d'un choc économique. Quant aux modèles d'entrées-sorties, ils sont appropriés pour analyser la relation entre l'économie et les sous-systèmes écologiques à travers les tableaux d'entrées-sorties (TES) à extensions environnementales (TES-EE) et sont particulièrement compatibles avec l'ACV.

7.4 Méthode proposée

La méthode proposée dans cette thèse est basée sur le cadre conventionnel de l'ACV défini par les normes internationales ISO 14040-44 (2006). Ainsi, ici, les quatre phases de la norme ISO14040-44 (telles que présentées dans la Figure 7.2) sont également conservées afin que la méthode soit cohérente avec le cadre commun actuellement appliqué par les praticiens. Comme présenté précédemment, un modèle économique basé sur les stocks et flux financiers qui permet aussi d'évaluer les effets sociaux est intégré dans l'étape de l'analyse de l'inventaire du cycle de vie, renforçant le côté interdisciplinaire de l'approche proposée dans cette thèse, regroupant les domaines économiques, environnementaux et sociaux.

7.4.1 Définition des objectifs et du champ de l'étude

Selon la norme ISO 14040, l'objectif d'une ACV définit l'application visée, les raisons de réaliser l'étude, le public et les objectifs de communication. La méthodologie ici proposée garde les mêmes exigences, aucune particularité n'étant ajoutée sur ce point. Pour la définition du domaine d'application, l'ISO 14040 exige, entre autres, la définition du système de produits, des limites du système et de l'unité fonctionnelle, abordées dans les sections suivantes.

7.4.1.1 Système de produit et limites du système

La norme ISO 14040 stipule que « idéalement, le système de produits devrait être modélisé de telle manière que les entrées et les sorties à sa frontière soient des flux élémentaires ». « Flux élémentaire » est le terme ISO 14040 pour un flux « puisé dans l'environnement sans transformation humaine préalable » ou « rejeté dans l'environnement sans transformation humaine ultérieure » (ISO 14040, clause 3.12), établissant ainsi la division traditionnelle entre l'économie et l'environnement. Si l'utilité et la pertinence ontologique de cette division ont été remises en cause (Weidema et al., 2018), il est encore courant de limiter l'analyse de l'économie aux fournisseurs qui vont modifier leur capacité de production en réponse à une variation cumulée de la demande pour le produit. Ces fournisseurs sont identifiés en retraçant chaque entrée de produit requise en amont tout au long de la chaîne d'activités. Le coût d'une activité (d'achat) est un revenu pour l'activité de fourniture. Pour chaque activité, une partie des revenus s'échappe sous forme de paiements aux employés et aux entrepreneurs, d'impôts et de rentes de ressources (ensemble appelés « facteurs primaires » ou « valeur ajoutée »). Dans un système fermé en régime permanent, toutes les recettes initiales doivent finalement quitter le système sous forme de paiements aux facteurs primaires, qui ne sont pas tracés plus en amont, fournissant ainsi une délimitation claire des activités incluses dans le système.

Les activités incluses dans le système de produits sont donc limitées à celles qui réagissent à l'évolution des revenus, correspondant aux effets de premier ordre des dépenses d'origine, tout en maintenant les dépenses globales constantes (hypothèse « ceteris paribus »). Implicitement, lors de la comparaison de produits à des prix différents, un système de produits inclura l'effet de rebond des prix de premier ordre, tout en excluant les effets de second ordre, tels que les changements dans les habitudes de consommation qui peuvent résulter de la redistribution des dépenses initiales sur les groupes de population qui reçoivent. Le revenu du facteur primaire, ou les effets de second ordre de la stimulation d'activités spécifiques, telles que l'éducation, la recherche et le développement technologique (Weidema et al., 2015).

Si cette délimitation aux effets de premier ordre fournit une délimitation sans ambiguïté des systèmes de produits, elle est néanmoins arbitraire et donc une délimitation intrinsèquement normative. La réticence à inclure les effets de second ordre dans l'ACV peut provenir de l'intuition que cela pourrait conduire à une expansion infinie du système pour inclure toutes les conséquences de toutes les activités « jusqu'à la fin du monde » (Weidema et al., 2015). Dans cette thèse, nous allons au-delà des frontières du système normatif et incluons les effets de redistribution des revenus, un type d'effets de second ordre (voir glossaire).

La première phase consiste alors à définir l'objectif et le champ d'application de l'étude. Pour cela, les raisons du choix de l'approche doivent être décrites, comme dans une ACV traditionnelle. Dans cette phase, l'unité fonctionnelle doit être définie et doit représenter le changement qui est étudié par l'ACV-C, ainsi que le délai de l'étude. Les autres caractéristiques

de cette première partie ne diffèrent pas significativement d'une ACV traditionnelle et pour cette raison ne seront pas détaillées ici.

La deuxième phase du cadre général consiste à analyser l'inventaire du cycle de vie. Cette phase est la plus difficile du point de vue des conséquences, car il faut y inclure les « effets indirects ». C'est donc dans cette phase qu'un modèle SFC est intégré, comme détaillé dans les sections suivantes. Il convient de souligner que la contribution majeure de la thèse réside dans cette phase de la méthodologie.

Une fois l'inventaire obtenu, l'évaluation des impacts peut être réalisée, en fonction des substances et des ressources qui ont été évaluées dans la deuxième phase.

7.4.1.2 Unité fonctionnelle

La norme ISO 14040 définit l'unité fonctionnelle comme « la quantification des fonctions identifiées » en tant que caractéristiques de performance pour fournir une unité de référence. Cependant, les normes ISO ne fournissent aucune définition claire sur les spécificités de l'approche conséquentielle. Récemment, dans leur revue, Schaubroeck et al. (2021) ont distingué la définition de l'unité fonctionnelle pour les approches attributionnelles et conséquentielles. Selon eux, l'unité fonctionnelle de l'ACV-C « analyse comment la décision modifie le système humain/industriel et son impact environnemental au niveau global », ce qui signifie que l'unité fonctionnelle doit représenter la décision étudiée, en termes de changements proposés au niveau global.

En pratique, l'unité fonctionnelle des nouvelles politiques doit refléter les changements de la demande résultant de la nouvelle politique. Lorsqu'il s'agit de substitutions, elles doivent être clairement décrites et représentées dans l'unité fonctionnelle, afin que les comparaisons soient obtenues de manière cohérente.

7.4.2 Inventaire du cycle de vie

L'idée de développer un modèle combinant des aspects d'analyse entrées-sorties et de cohérence stock-flux, et des modèles de processus, comme l'ACV, est de tirer parti de leurs avantages et de fournir un outil complet et détaillé d'aide à la décision. *Five Assets Unified Stock-flow Transactions* (FAUST) représente cette idée conceptuelle initialement développée par Weidema (2019). Ce modèle aurait autant de couches que nécessaire pour représenter la perturbation aux fins de l'utilisateur, par exemple, l'une de ces couches pourrait être la masse sèche, pour représenter les flux physiques et les stocks d'une perturbation (Weidema, 2019).

Dans une matrice FAUST, les colonnes représentent les activités qui affectent chacun des cinq actifs : ressources naturelles, capital manufacturé, capital humain, capital de réseau social et capital financier. Les activités qui composent l'idée conceptuelle de FAUST sont les activités de l'écosphère, les activités de production et de loisirs, l'exportation, l'importation et les

variations de stocks. Le cadre conceptuel de FAUST est basé sur des modèles cohérents stock-flux. Un bilan alors est effectué pour chaque couche, en considérant que chaque sortie d'un actif dans une colonne doit être une entrée dans la même ligne mais pour une autre activité.

Compte tenu de la complexité de FAUST pour la prise en compte de toutes les interactions, cette thèse s'intéresse au capital financier, servant d'intermédiaire aux autres activités et pouvant ainsi suivre l'évolution des flux, et par conséquent l'évolution des stocks. La meilleure représentation de FAUST dans les modèles SFC est la Matrice des Flux de Transactions (MFT), où les flux, ainsi que les variations de stocks, sont pris en compte (Godley & Lavoie, 2007).

La combinaison d'éléments de l'AES et du SFC a été menée dans des recherches antérieures, par exemple, Berg et al. (2015) présentent une méthodologie de modélisation de différentes natures de flux, basée sur un modèle AES-SFC, et appliquent la méthodologie dans une économie composée de deux secteurs. Dans cette thèse, nous combinons la méthodologie proposée par Berg et al. (2015) pour évaluer les effets de premier ordre avec des tableaux multirégionaux d'entrées-sorties à extensions environnementales (TMES-EE), et nous allons plus loin pour inclure les effets de second ordre, comme nous l'appelons « modèle de (re)distribution des revenus ».

Les TMES-EE sélectionnées pour les besoins de cette thèse sont l' EXIOBASE, base de données open-source TMES-EE développée par un consortium de plusieurs instituts de recherche, financée par des projets consécutifs dans le cadre du 7e programme-cadre de la Commission européenne. La première version d'EXIOBASE (EXIOBASE 1) a été développée entre 2007 et 2011 à la suite du projet EXIOPOL (de Koning et al., 2011) et couvre pour l'année 2000, 43 pays, 1 région reste du monde, 200 produits, 163 industries, 15 types d'utilisation des terres, 48 types de matières premières et 172 types d'eau utilisée. En 2013, EXIOBASE 2 a été lancée à la suite du projet CREEA (Tukker et al., 2013), pour l'année 2007 avec les mêmes caractéristiques que la version précédente, mais couvrant 4 autres régions du reste du monde.

La version la plus récente d'EXIOBASE (EXIOBASE 3) a été développée dans le cadre du projet DESIRE (Commission européenne, 2016). Cette version présente les TMES-EE sous forme monétaire et hybride, et les données sont disponibles pour la période de 1995 à 2011. Elle couvre 44 pays, 5 régions du reste du monde, 164 industries, 200 produits, 3 niveaux de compétences professionnelles par sexe, 417 catégories d'émissions et 662 catégories de matériaux et de ressources. Les séries de données monétaires sont disponibles dans le module python **pymrio** (Stadler, 2021), dans lequel sont inclus des estimations basées sur une variété de données à l'appui, telles que des données commerciales et macroéconomiques, allant jusqu'en 2022.

Idéalement, lors de la réalisation d'une ACV, il est recommandé d'utiliser les tableaux d'entrées-sorties produit par produit, et notamment la « technologie des sous-produits » pour l'approche conséquentielle. Néanmoins, la seule version couvrant ces deux critères est la

version hybride fournissant des données à partir de 2011. Par conséquent et considérant que la couverture temporelle de la version pymrio est plus appropriée pour l'étude de cas, le tableau d'entrées-sorties monétaire d'EXIOBASE 3.8.1 (ci-après EXIOBASE) a été sélectionné pour effectuer la modélisation présentée dans cette thèse, malgré le fait qu'il enfreint certaines des caractéristiques souhaitées de la modélisation conséquentielle.

En ce qui concerne les extensions environnementales, deux types sont disponibles : la comptabilité basée sur la production (CBP) et la comptabilité basée sur la consommation (CBC). La première tient compte des activités de production qui se déroulent à l'intérieur des frontières d'un pays, tandis que la CBC prend également en compte les pressions environnementales liées au commerce (importations et exportations) (Stadler et al., 2015). Dans la méthodologie développée pour cette thèse, les impacts environnementaux sont calculés en multipliant le changement de production (obtenu par l'inverse de Leontief) par une matrice de coefficients environnementaux normalisés, qui peut être une CBP ou une CBC. La variation de la production totale reflète la chaîne de produits et de services concernés (sur le territoire national mais aussi ailleurs).

Par conséquent, la multiplication de la variation de la production totale par les émissions de l'analyse coûts-avantages refléterait les émissions directes et indirectes (et serait équivalente aux émissions de l'analyse coûts-avantages). Cela est dû au fait que chaque produit est caractérisé par ses propres intrants nationaux et importés, qui sont également caractérisés par leurs intrants nationaux et importés (et ainsi de suite). Par conséquent, pour éviter le double comptage, dans cette thèse, la CBP a été choisie pour obtenir les impacts environnementaux. Une analyse de sensibilité sur les émissions de GES a également été réalisée pour comparer les résultats avec la version hybride.

La Figure 7.5 présente le cadre général de la méthode proposée, qui se compose de cinq étapes. La première chose à faire est de définir la perturbation exogène, en fonction des objectifs de l'étude. La perturbation doit représenter l'unité fonctionnelle de l'étude. La deuxième étape consiste à définir les transactions qui feront partie de l'étude et à sélectionner les secteurs institutionnels pertinents pour l'étude. La troisième étape est l'intégration d'un modèle de distribution monétaire. La quatrième étape consiste à comptabiliser les changements de flux dans une MFT et à analyser les changements de stocks qui affecteront un autre cycle de distribution, en revenant à l'étape 3. Le lien entre les étapes 4 et 3 peut être considéré comme une cinquième étape, comme présenté dans la Figure 7.5.

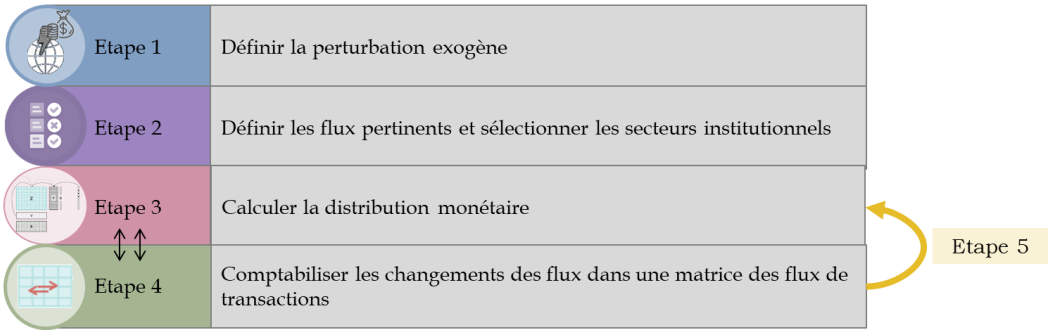


Figure 7.5 | Etapes de la méthode développée pour l'ICV

7.4.2.1 Etape 1 : Définir la perturbation exogène

Une perturbation économique est définie comme tout changement qui affecte l'économie (Mankiw, 2009). Les perturbations exogènes se produisent en dehors de l'industrie ou du pays mais peuvent avoir des effets sur les marchés au sein d'une industrie ou d'un pays (UNESCWA, 2020). Cette étape est alignée sur la définition des objectifs et de la portée de l'étude (étape 1 du cadre général de l'ACV fourni dans la norme ISO 14040-44).

L'unité fonctionnelle représente la perturbation économique et peut être quantifiée en fonction de la taille et du niveau d'agrégation des tableaux d'entrée-sortie utilisés. Idéalement, les produits impactés devraient être endogénéisés en utilisant les données marginales les plus réalistes pour représenter les étapes du cycle de vie du produit donné.

Dans le cas de cette thèse, les produits affectés par la perturbation exogène ont été sélectionnés parmi les activités qui sont incluses dans EXIOBASE 3. La liste complète des activités couvertes par EXIOBASE est disponible dans l'annexe (Appendix 2 – EXIOBASE 3 activities)

7.4.2.2 Etape 2 : Définir les flux pertinents et sélectionner les secteurs institutionnels pertinents

Une MFT peut inclure autant de transactions que nécessaire pour représenter l'économie en fonction des besoins de l'étude. La sélection des transactions est donc basée sur l'objectif de l'étude. Godley et Lavoie (2007) fournissent dans leur livre plusieurs exemples de situations, des plus simples aux plus sophistiquées, où les transactions et les secteurs sont sélectionnés correctement. Une preuve de concept du modèle de (re)distribution est présentée dans un article complémentaire à cette thèse où l'objectif de l'étude était de tester la méthode dans une économie fermée simplifiée composée de six industries, de banques et de ménages à trois niveaux de revenus[23].

Les principaux textes internationalement reconnus qui guident les études macroéconomiques sont le Système Européen des Comptes (SEC) (European Commission,

[23] L'article mentionné est (Almeida et al., 2022)

2013), le Système de Comptabilité Nationale (SCN) de 2008 (United Nations, 2008), et le Manuel de la balance des paiements et de la position extérieure globale (BPM6), du Fond Monétaire International (FMI) (IMF, 2009). La base de données d'Eurostat (Eurostat, 2022) fournit des ensembles de données en source ouverte qui sont cohérents avec ces approches méthodologiques comptables pour les transactions ainsi que les bilans des pays.

Les unités institutionnelles se distinguent des secteurs, comme suit : une unité institutionnelle est une entité économique capable de posséder des biens et des actifs, de contracter des dettes et de s'engager dans des activités économiques et des transactions avec d'autres unités de plein droit (European Commission, 2013). Les secteurs institutionnels, quant à eux, sont des groupes d'unités institutionnelles ayant des formes de comportement économique similaires caractérisées par leur fonction principale et la nature de leur activité (INSEE, 2021a). Par conséquent, les unités institutionnelles résidentes sont regroupées en cinq secteurs domestiques : sociétés non financières (SNF), sociétés financières (SF), administrations publiques (AP), ménages (MS), institutions sans but lucratif au service des ménages (ISBLSM). Les unités non résidentielles sont regroupées dans le secteur du reste du monde (ROW).

Dans cette thèse, le premier critère de sélection des transactions qui sont incluses dans le modèle proposé est basé sur la disponibilité des données. EXIOBASE fournit les flux suivants :

- Impôts sans les subventions sur les produits achetés.
- Autres impôts nets sur la production
- Rémunération des employés ; salaires, traitements et cotisations sociales des employeurs : Faible, moyen et haut niveau de qualification
- Excédent d'exploitation : Consommation de capital fixe
- Excédent d'exploitation : Loyers fonciers
- Excédent d'exploitation : Redevances sur les ressources
- Excédent d'exploitation : Excédent net d'exploitation restant
- Dépenses de consommation finale des ménages
- Dépenses de consommation finale des organisations sans but lucratif au service des ménages (ISBLSM)
- Dépenses de consommation finale des administrations publiques
- Formation brute de capital fixe
- Variations des stocks
- Variations des objets de valeur

Le deuxième critère est la matérialité des transactions vis-à-vis l'économie totale. Pour cela, une analyse a été conduite en fonction des transactions disponibles pour la France, à partir de données obtenues par le SCN. Les transactions retenues sont listées ci-dessous :

- La dépense de consommation finale, qui est incluse dans EXIOBASE3.

- La formation brute de capital, qui est incluse dans EXIOBASE3
- Les exportations de biens et services (obtenus à partir d'EXIOBASE)
- Les importations de biens et de services (obtenus à partir d'EXIOBASE)
- la valeur ajoutée brute (obtenus à partir d'EXIOBASE)
- Salaires, inclus dans EXIOBASE3
- Cotisations sociales des employeurs, incluses dans EXIOBASE3 (agrégées aux salaires)
- Impôts sur les produits, inclus dans EXIOBASE3
- Intérêts
- Revenus de la propriété attribués aux détenteurs de polices d'assurance
- Impôts courants sur le revenu, le patrimoine
- Cotisations sociales
- Prestations sociales autres que les transferts sociaux en nature
- Autres transferts courants

Les secteurs retenus sont : les ménages désagrégés par niveau de qualification proposé par l'Organisation Internationale du Travail (OIT) : faiblement qualifiés (MS-FS), moyennement qualifiés (MS-MQ) et hautement qualifiés (MS-HQ), l'administration publique (AP), les sociétés financières (SF) et non-financières (SNF) et le reste du monde (ROW).

7.4.2.3 Etape 3 : Calculer la distribution monétaire

Le modèle de distribution est basé sur l'IOA, de sorte que la distribution monétaire est calculée à partir de la modélisation IO classique et comprend autant d'activités que celles contenues dans le TES Tout d'abord, la matrice des coefficients techniques (A) doit être définie. Elle contient le ratio des entrées de la branche "i" à la branche "j" (z_{ij}) par rapport aux sorties totales de la branche "j" (x_j) et s'obtient par l'équation 7-1. EXIOBASE fournit dans son jeu de données cette matrice.

$$A = \frac{a_{ij}}{x_j} \qquad \text{Equation 7-1}$$

Un changement marginal de la demande finale affectera les besoins en intrants directs et indirects, obtenus par l'inverse de Leontief $L = (I - A)^{-1}$. Par conséquent, les changements dans le vecteur des sorties totales (x'), également connus sous le nom de facteurs d'échelle, sont calculés par l'équation 7-2.

$$x' = LF \qquad \text{Equation 7-2}$$

Ces changements dans la production totale des industries affectent le montant d'argent reçu par les employés des industries, en gardant les mêmes proportions entre les groupes de revenus au sein de chaque industrie qu'avant le choc. Cela peut être compris soit comme un changement proportionnel du nombre de travailleurs dans les industries affectées, soit comme un changement proportionnel des salaires. Cet impact est calculé en multipliant la matrice des

coefficients normalisés de la valeur ajoutée brute (B), où $\hat{b}_j = \frac{b_j}{xj'}$, par les changements dans le vecteur de la production totale (x'), comme présenté dans l'équation 7-3.

$$G = \hat{B}x' \qquad \text{Equation 7-3}$$

La matrice G représente les variations du revenu des facteurs primaires, c'est-à-dire le revenu du travail perçu par les ménages travaillant dans l'industrie "j", après toute redistribution fiscale du revenu, les variations des taxes sur les produits payées par les industries, et les variations de l'excédent d'exploitation associé à chaque activité.

L'ICV est obtenu en élargissant la matrice G pour inclure des informations environnementales. Pour cela, appelons E la matrice contenant les émissions de substances et les ressources naturelles associées à chaque activité. Comme pour la valeur ajoutée brute, une matrice de coefficients environnementaux normalisés $\hat{E}$) est nécessaire, où $\hat{e}_j = \frac{e_j}{xj}$. Par conséquent, l'ICV, représenté par la matrice D, est obtenu en multipliant la matrice $\hat{E}$ par les nouvelles sorties, comme présenté dans l'équation 7-4.

$$D = \hat{E}x' \qquad \text{Equation 7-4}$$

7.4.2.4 Etape 4 : Comptabiliser les changements des flux dans une matrice des flux de transactions

À chaque tour de distribution, les changements dans les flux et les stocks doivent être comptabilisés dans une matrice des flux de transactions (MFT), comme montre le Tableau 7.3. Cette étape se déroule parallèlement à l'étape 3 pour garantir la cohérence de toutes les transactions, à partir de la perturbation. La difficulté consiste à savoir qui reçoit l'argent et qui le paie.

Tableau 7.3 | Matrice des flux de transactions et les paramètres utilisés (Source : Compilation de l'auteur à partir des tableaux SCN et d'EXIOBASE)

Transaction	SNF	SF	GG	MS			RoW	Somme
				FQ	MQ	HQ		
Dépenses de consommation finale	$+C^R{}_{NFC}$			$-C^U{}_{HH,LS}$	$-C^U{}_{HH,MS}$	$-C^U{}_{HH,HS}$		0
Formation brute de capital	$+GCF^R{}_{NFC}$		$-GCF^U$	$-GCF^U{}_{HH,LS}$	$-GCF^U{}_{HH,MS}$	$-GCF^U{}_{HH,HS}$		0
Exportations de biens et de services	$+Ex^R{}_{NFC}$						$-Ex^U{}_{ROW}$	
Importations de biens et de services	$-\mathfrak{I}^U{}_{NFC}$						$+\mathfrak{I}^R{}_{ROW}$	0
Excédent d'exploitation	$-OS^U{}_{NFC} + OS^R{}_{NFC}$	$+OS^R{}_{FC}$	$+OS^R$	$+OS^R{}_{HH,LS}$	$+OS^R{}_{HH,MS}$	$+OS^R{}_{HH,HS}$		0

Salaires et rémunérations	$-W^U{}_{NFC}$			$+W^R{}_{HH,LS}$	$+W^R{}_{HH,MS}$	$+W^R{}_{HH,HS}$		0
Cotisations sociales de l'employeur	$-ESC^U{}_{NFC}$		$+ESC^R$					0
Impôts sur les produits	$-TxP^U{}_{NFC}$		$-TxP^R$					0
Autres impôts sur la production	$-OTx^U{}_{NFC}$		$-OTx^R$					0
Intérêts sur les prêts	$-IL^U{}_{NFC}$	$-IL^R{}_{FC}$	$-IL^U{}_{NFC}$					0
Intérêts sur les dépôts	$+ID^R{}_{NFC}$	$-ID^U{}_{FC}$		$+ID^R{}_{HH,LS}$	$+ID^R{}_{HH,MS}$	$+ID^R{}_{HH,HS}$		0
Impôts actuels sur le revenu, le patrimoine, etc.			$+TI^R$	$-TI^U{}_{HH,LS}$	$-TI^U{}_{HH,MS}$	$-TI^U{}_{HH,HS}$		0
Cotisations sociales			$+SC^R$	$-SC^U{}_{HH,LS}$	$-SC^U{}_{HH,MS}$	$-SC^U{}_{HH,HS}$		0
Prestations sociales			$-SB^U{}_{NFC}$	$+SB^R{}_{HH,LS}$	$+SB^R{}_{HH,MS}$	$+SB^R{}_{HH,HS}$		0
Autres			$+CT^R$				$-CT^U{}_{ROW}$	0
Dépôts	$-Dp^U{}_{NFC}$	$+Dp^R{}_{FC}$	$-Dp^U$	$-Dp^U{}_{HH,LS}$	$-Dp^U{}_{HH,MS}$	$-Dp^U{}_{HH,HS}$	$-Dp^U{}_{ROW}$	0
Dette	$-Db^U{}_{NFC}$	$-Db^U{}_{FC}$	$+Db^R$ $-Db^U$	$+Db^R{}_{HH,LS}$	$+Db^R{}_{HH,MS}$	$+Db^R{}_{HH,HS}$	$-Db^U{}_{ROW}$	0
Somme	0	0	0	0	0	0	0	

Les variations des stocks (valeur nette) sont le résultat de l'équilibre monétaire des flux, c'est-à-dire de la valeur de prêt net ou d'emprunt net de chaque secteur institutionnel. Une hypothèse commune est que les SNF reçoivent tout l'argent provenant de la consommation, de la formation de capital et des exportations et paient les importations. En contrepartie, ils redistribuent une partie de la valeur ajoutée aux autres secteurs institutionnels. Dans le cas de la France, par exemple, la redistribution de la valeur ajoutée brute en 2020 suit les proportions suivantes : 10% pour les SF, 44% pour les AP, 42% pour les MS et 4% pour les ISBLSM, obtenues à partir des valeurs présentées dans l'annexe (Appendix 3).

Ici ce raisonnement est suivi, les SNF reçoivent toutes les variations des transactions des éléments de la demande finale plus les exportations, paient pour les importations de produits et redistribuent une partie de la valeur ajoutée à travers l'excédent d'exploitation. Les taux appliqués pour distribuer l'excédent d'exploitation sont obtenus à partir des contributions des secteurs institutionnels à la valeur ajoutée brute.

L'excédent d'exploitation perçu par les ménages doit être ventilé selon les groupes de revenus. Il y a plusieurs façons possibles de procéder, qui affectent différemment la richesse nette de chaque groupe de revenus et les cycles suivants de consommation induite. Les trois scénarios définis pour l'excédent d'exploitation sont les suivants :

- Scénario 1 : l'excédent d'exploitation associé à chaque produit est distribué aux trois groupes de revenus suivant les mêmes proportions que les salaires et traitements sont versés à chaque groupe de revenus.
- Scénario 2 : la totalité de l'excédent d'exploitation est perçue par les ménages hautement qualifiés.
- Scénario 3 : tout le surplus d'exploitation est épargné par les ménages (sa forme agrégée)

Dans le scénario 1, pour les activités où il n'y a pas de données sur la rémunération des employés et où l'activité présente un excédent d'exploitation, l'allocation est effectuée comme si tout l'excédent d'exploitation allait au groupe de revenu de qualification haute. C'est le cas pour 51 activités, par exemple les services d'organisation des membres au Danemark.

La base de données EXIOBASE fournit des informations sur les principaux flux qui sont inclus dans la méthode proposée. Cependant, il n'y a pas d'informations concernant les stocks. Pour cela, une base de données de stocks a été construite (Section 3.5).

Les changements dans les stocks peuvent induire la consommation et/ou l'investissement, ce qui entraîne des impacts environnementaux. À la fin du premier cycle de distribution monétaire, l'argent cumulé des ménages (dans le cas d'un choc exogène positif) entraînerait une fausse augmentation de la richesse nette, car l'argent reçu des ménages en tant que salaire est utilisé pour acheter des biens et services de consommation. Par conséquent, les variations des stocks au premier tour de chaque période sont temporaires et provoquent un effet induit, dans lequel une redistribution monétaire a lieu.

7.4.2.5 Etape 5 : Calculer la redistribution monétaire

Les ménages modifient leur consommation en fonction de la variation de leur valeur nette par rapport au cycle précédent. En réalité, les ménages épargnent une partie de leur revenu supplémentaire et une autre partie est dépensée en biens de consommation. Cette consommation induite comprend les déplacements de la consommation entre les industries en raison des différentes habitudes de dépenses des trois groupes de revenus. Ici, une « période de distribution » comprend les changements dans la rémunération des employés résultant de la perturbation (1er tour) et la consommation induite résultant des changements dans le revenu (2ème tour).

La consommation des ménages n'est ici qu'une fonction du revenu du travail, tandis que leur revenu de la propriété est entièrement réinvesti. La variation de la demande finale (F) est donc obtenue à partir de la fonction de consommation décrite dans l'équation 7-5.

$$F = \mathcal{C}.H \qquad \text{Equation 7-5}$$

La matrice $\mathcal{C}$ représente les modèles de consommation marginale, qui peuvent être obtenus à partir des statistiques nationales. Ces matrices doivent être désagrégées en fonction du nombre de niveaux de revenus des ménages et du nombre d'activités qui sont incluses dans le TES. La matrice H représente les dépenses du second tour, c'est-à-dire la partie du revenu des ménages qui sera utilisée pour la consommation au second tour ($H_i = Dp^U{}_i.\alpha_i$, où Dp^U représente la variation des dépôts comptabilisés au tour précédent, α est la propension à consommer à partir du revenu supplémentaire, tous deux désagrégés par niveau de revenu. La variation des dépôts est enregistrée comme une « utilisation » dans la MFT car elle est temporairement transférée sur leurs comptes courants.

Cette consommation induite est le nouveau vecteur de perturbation pour le tour suivant, et de manière répétée pour les tours de redistribution (r+1), comme présenté dans l'équation 7-6.

$$F^{r+1} = \mathcal{C}H^r \qquad \text{Equation 7-6}$$

Les changements dans les stocks (richesse nette) des autres secteurs institutionnels peuvent également présenter des effets de second ordre, tels que l'investissement et la croissance. Dans cette thèse, nous nous limitons à inclure l'effet de redistribution des revenus et laissons la croissance de la productivité et l'inclusion d'une fonction d'investissement à des recherches futures.

7.4.3 Evaluation de l'impact environnemental

L'inventaire du cycle de vie est obtenu en étendant la matrice G pour inclure les émissions de substances et la consommation de ressources, également connues sous le nom de facteurs de stress biophysiques (matrice E). EXIOBASE disponible dans *pymrio* fournit deux types d'extensions environnementales : les émissions de substances et la consommation de ressources par activité (jeu de données satellite) et les indicateurs d'impact caractérisés par activité (jeu de données d'impact). Ce dernier présente les indicateurs d'impact déjà caractérisés par les méthodes d'évaluation d'impact habituelles, y compris 123 catégories d'impact, provenant de CML, Ecoindicator 99, ILCD, IPCC, et autres. Le premier jeu de données satellitaires comprend 1090 émissions de substances et consommation de ressources naturelles, parmi lesquelles le dioxyde de carbone, le méthane, les émissions de particules, la consommation d'eau, et bien d'autres. La liste complète est disponible sur le site web de pymrio.

Théoriquement, toute méthode LCIA peut être appliquée pour caractériser les émissions et les ressources qui sont incluses dans la base de données. Dans cette thèse, la méthodologie développée est appliquée dans une étude de cas dans le secteur de la construction, donc l'évaluation de l'impact environnemental donne la priorité aux catégories d'impact

particulièrement pertinentes pour le secteur de la construction, à savoir la consommation d'énergie, les émissions de GES, et les déchets.

En ce qui concerne les émissions de GES, il y a deux façons d'obtenir cet indicateur dans EXIOBASE : calculer les émissions de GES en appliquant les facteurs de caractérisation appropriés aux substances émises à partir de l'ensemble de données satellitaires, ou sélectionner l'indicateur de changement climatique à partir de l'ensemble de données d'impact. Ce dernier comprend 10 indicateurs de changement climatique, dont trois issus de la méthode ILCD (un point médian et deux points finaux : santé humaine et écosystèmes) ; un indicateur d'émissions de GES obtenu en utilisant les facteurs de caractérisation du cinquième rapport d'évaluation du GIEC (AR5), avec un potentiel de réchauffement global (PRG) de 100 ans ; et cinq indicateurs d'émissions de GES issus de la méthode CML (approche orientée problème), soit un de référence et quatre non de référence, en variant l'horizon temporel du PRG (20, 100 et 500 ans).

En théorie, si nous appliquons les mêmes facteurs de caractérisation que les méthodes sélectionnées par EXIOBASE, les résultats seront les mêmes pour les deux options. Pour cette raison, le choix fait dans cette thèse a été de sélectionner un des indicateurs de changement climatique de l'ensemble des données d'impact, à savoir le point médian du changement climatique de l'ILCD, avec un PRG de 100 ans, qui est celui requis dans la déclaration du profil environnemental des produits de construction.

Pour la consommation d'énergie, il n'y a pas de catégorie d'impact ayant déjà évaluée dans la base de données d'impact. Cependant, une mise à jour des facteurs de caractérisation pymrio a récemment été lancée pour relier EXIOBASE à la méthode IMPACT World+2 . Dans cette matrice mise à jour, il existe des facteurs de caractérisation pour la prise en compte de l'indicateur énergétique appelé utilisation d'énergie fossile et nucléaire, qui caractérise la consommation d'énergie non seulement à partir des apports énergétiques de la nature, mais aussi pour l'extraction de combustibles fossiles (flux domestiques utilisés et non utilisés). Ces facteurs de caractérisation ont été utilisés dans la thèse.

Le TES monétaire d'EXIOBASE disponible pour 2020 dans *pymrio* ne donne aucune information sur les déchets produits en masse. La version hybride, en revanche, fournit des informations sur les déchets fournis et utilisés par chaque activité et par les demandes finales (Stadler et al., 2018), cependant, la dernière version d'EXIOBASE couvre l'année 2011. Les déchets sont définis dans EXIOBASE comme « une matière à traiter qui comprend toutes les matières qui nécessitent un retraitement ultérieur afin d'être transformées en nouveaux produits, en émissions ou en ajouts de stocks dans les décharges » (Stadler et al., 2018). Les données sont disponibles sous les formes suivantes : les déchets fournis par activité, les déchets fournis par la demande finale, les déchets fournis à partir de matériaux accumulés précédemment dans la société, et l'utilisation des déchets par activités. Le côté utilisation concerne les activités de traitement des déchets, tandis que le côté offre concerne les autres

activités, les ménages, les institutions sans but lucratif au service des ménages et les administrations publiques.

Par conséquent, les intensités de l'offre de déchets (masse totale produite par production monétaire totale) fournies par activité en 2011 ont été utilisées dans la thèse. La liste des types de déchets qui sont analysés dans la thèse est présentée ci-dessous :

- Déchets alimentaires
- Fumier
- Déchets textiles
- Déchets de bois
- Déchets de papier
- Déchets de plastique
- Déchets de verre
- Cendres
- Déchets d'acier, d'aluminium, de plomb, de cuivre et de métaux non ferreux
- Déchets de métaux précieux
- Matériaux de construction et déchets miniers (à l'exclusion des matériaux miniers non utilisés)
- Huiles et déchets de matières dangereuses
- Eaux usées
- Déchets miniers
- Déchets non utilisés

7.4.4 Base de données des stocks

L'objectif de la construction de la « base de données des stocks » est de fournir des informations sur les agents affectés par les changements dans les stocks des secteurs institutionnels inclus dans l'étude. Pour cela, il faut construire une matrice « de-qui-pour-qui » entre les secteurs institutionnels et les pays. Les investisseurs peuvent placer leur argent en utilisant différents instruments financiers, dans le but de recevoir un revenu résultant de l'investissement. Par exemple, les actions entraînent la distribution des revenus des sociétés, tandis que les dépôts, les titres de créance et les prêts donnent lieu à des intérêts payés/reçus (IMF, 2015). Lorsque l'on investit dans d'autres pays, la traçabilité est une question importante, ainsi les **instruments financiers** sont classés en suivant les normes internationales. La sixième édition du Manuel de la balance des paiements et de la position extérieure globale (BPM6) fournit les définitions qui sont utilisées dans les comptes internationaux, où l'investissement est distingué en cinq catégories : **investissements directs**, **investissements de portefeuille**, **produits financiers dérivés**, **autres investissements** et **avoirs de réserve** (IMF, 2009).

Les **investissements directs** correspondent à la « catégorie d'investissements transfrontaliers associée au fait qu'un résident d'une économie a le contrôle ou un degré

significatif d'influence sur la gestion d'une entreprise qui est résidente d'une autre économie », selon le BPM6. Le principal instrument de l'investissement direct est l'achat d'actions d'une société, le plus souvent par des entreprises qui créent des filiales dans d'autres pays. La base de données statistiques mondiale concernant les investissements directs est l'enquête coordonnée sur les investissements directs (CDIS), dont l'objectif est de fournir des données transfrontalières « de-qui-à-qui ».

Les **investissements de portefeuille** sont définis dans le BPM6 comme « des transactions et positions transfrontalières portant sur des titres de créance ou de participation, autres que ceux inclus dans les investissements directs ou les avoirs de réserve ». L'instrument le plus courant de cette catégorie est l'achat de titres de participation d'une société. Les titres sont des instruments de dette et de capitaux propres qui sont négociables, échangeables et présentent une valeur monétaire, comme les actions et les obligations (IMF, 2009). La base de données statistique mondiale concernant les investissements de portefeuille est l'enquête coordonnée sur les investissements de portefeuille (CPIS), qui fournit des données sur les avoirs de l'économie en titres d'investissements de portefeuille, comme les actions et les parts de fonds de placement et les titres de créance par échéance.

Selon le BPM6, les **produits financiers dérivés** couvrent les instruments financiers qui sont liés à un autre instrument ou indicateur financier ou à une marchandise spécifique et par lesquels des risques financiers spécifiques (tels que le risque de taux d'intérêt, le risque de change, le risque de prix des actions et des marchandises, le risque de crédit, etc.

Les **avoirs de réserve** sont définies dans le BPM6 comme les « avoirs extérieurs qui sont facilement disponibles et contrôlés par les autorités monétaires pour répondre aux besoins de financement de la balance des paiements, pour intervenir sur les marchés des changes afin d'influer sur le taux de change de la monnaie, et à d'autres fins connexes (telles que le maintien de la confiance dans la monnaie et l'économie, et servir de base aux emprunts à l'étranger) ». Ils ne comprennent que les actifs réellement existants et doivent être définis en monnaie étrangère. Un exemple courant est l'or monétaire appartenant aux autorités monétaires (banque centrale) constitué de lingots d'or facilement disponibles sur demande (liquidité) (IMF, 2009).

Les **autres investissements** sont une catégorie résiduelle, i.e, toutes les transactions ne correspondant pas aux caractéristiques des quatre autres catégories sont classées comme autres investissements. Elle comprend donc la **monnaie et les dépôts**, **les prêts** et les assurances-vie, par exemple, qui représentent certains des instruments qui sont affectés par des variations marginales des stocks.

Idéalement, la matrice inter-pays « de-qui-à-qui » serait nécessaire pour chaque instrument de dette, défini comme des transactions nécessitant le paiement de la valeur du principal et des intérêts à un moment défini dans le futur (IMF, 2015). Cependant, en raison d'un manque de données, une méthode a été développée pour construire la matrice inter-pays

« de-qui-à-qui » pour les instruments de dette, en général. Les références utilisées sont des données statistiques internationales fournies par les instituts financiers internationaux ainsi que des statistiques nationales provenant des banques centrales nationales et des instituts nationaux de statistique et d'économie (comme la Banque de France et l'INSEE pour la France).

Le premier défi a été de sélectionner les pays à inclure dans la collecte de données. Comme la méthode développée dans cette thèse est appliquée dans une étude de cas en France, les engagements français vis-à-vis des non-résidents ont été utilisés comme référence. La sélection des pays a été faite en utilisant l'instrument financier **autres investissements** présentés dans la position extérieure globale de la France, qui peut être obtenue à partir de la base de données de la banque centrale française. Cet instrument financier a été choisi car il s'agit de la catégorie où la dette est l'instrument prédominant. Par exemple, en 2020, l'économie totale de la France avait 2 843 159 millions d'euros d'engagements sous forme de titres de créance, sur un total d'autres investissements de 2 855 116 millions d'euros, soit plus de 99 %, tandis que les titres de créance représentaient 75 % du total des engagements en investissements de portefeuille (2 755 665 millions d'euros sur 3 673 313 millions d'euros).

Tous les pays détenant au moins 1 % du passif de la France en 2020 ont été sélectionnés, à l'exception des centres financiers extraterritoriaux. Ces derniers ont été exclus en raison de la difficulté d'obtenir des données transparentes et fiables les concernant. En plus, la base de données inclut également les économies mondiales qui sont exclues par le critère de coupure mais qui représentent une relation commerciale importante avec la France. La liste des pays ajoutés est la suivante : Inde, Brésil, Pologne, Canada, Russie et Australie. Ainsi, au total, cette base de données de stocks comprend 19 pays, à savoir (avec les codes ISO 3166 respectifs) :

- France (FR)
- Royaume-Uni (GB)
- États-Unis d'Amérique (US)
- Allemagne (DE)
- Luxembourg (LU)
- Pays-Bas (NL)
- Italie (IT)
- Suisse (CH)
- Espagne (ES)
- Irlande (IE)
- Belgique (BE)
- Japon (JP)
- Chine (CN)
- Inde (IN)
- Brésil (BR)
- Pologne (PL)
- Canada (CA)
- Russie (RU)
- Australie (AU)

Tout d'abord, un examen de la disponibilité des données sur la dette extérieure a été effectué, qui est définie par le FMI comme l'encours des dettes qui exigent le paiement du principal et ou des intérêts par le débiteur à un moment donné dans le futur et qui sont détenues à des non-résidents par des résidents de l'économie (IMF, 2014). Les statistiques de la dette extérieure sont mesurées et suivies par plusieurs agences internationales dans le

monde, les deux principales bases de données accessibles au public sont les statistiques trimestrielles de la dette extérieure (QEDS) de la Banque mondiale et le *Joint External Debt Hub* (JEDH).

Le QEDS a pour objectif de faciliter la comparaison et l'analyse de la dette extérieure, en fournissant une base de données initialement développée par le FMI en collaboration avec la Banque mondiale, et maintenant maintenue par cette dernière. Elle contient des statistiques sur la dette extérieure des pays qui souscrivent à la norme spéciale de diffusion des données du FMI et également de ceux qui participent au système général de diffusion des données du FMI, rassemblant les données publiées individuellement par chaque pays (IMF, 2020; World Bank, 2021).

Par conséquent, les données sur la dette extérieure brute des dix-neuf pays sélectionnés de 2008 à 2020 ont été extraites du QEDS, à l'exception de la Chine, pour laquelle les informations ne sont disponibles que de 2015 à 2020. Les secteurs institutionnels inclus dans la QEDS sont les administrations publiques, la banque centrale, les sociétés de dépôt (hors banque centrale), les investissements directs et les autres secteurs.

La source la plus classiquement utilisée pour obtenir des informations sur la dette intérieure d'une économie est le Système de Comptabilité Nationale (SCN), qui fournit la dette totale détenue ventilée par secteurs institutionnels, en particulier les bilans. Ceux-ci présentent le total des actifs et le total des passifs détenus/émis par les secteurs institutionnels résidents (désagrégés) vis-à-vis des non-résidents (agrégés).

Par conséquent, à partir des bilans du SCN, l'information sur le degré d'endettement de chaque secteur institutionnel résident est disponible, mais il n'y a pas d'information concernant la contrepartie (par exemple, qui émet l'actif, si l'émetteur est résident ou non, etc.) Considérant que la QEDS fournit la dette totale détenue par les résidents (désagrégée en secteurs institutionnels) vis-à-vis des non-résidents, une simple soustraction entre les chiffres du bilan financier et la dette extérieure donnerait la répartition entre dette extérieure et intérieure. Le problème découlant de cette simple soustraction est que la ventilation sectorielle est différente entre les deux sources de données. Pour cela, une méthode d'allocation a été proposée et est présenté dans le Tableau 7.4.

Tableau 7.4 | Méthode d'allocation pour la dette intérieure et extérieure (Source : hypothèses faites par l'auteur basées sur l'avis d'experts)

Secteurs institutionnels sur SCN	Secteurs sur QEDS
Administration publique	= Administration publique
Ménages et ISBLSM	= 0
Sociétés financières	= Banque centrale + Sociétés de dépôt + μ ·Investissements directs + φ ·Autres secteurs
Sociétés non financières	= $(1-\mu)$ ·Investissements directs + $(1-\varphi)$ ·Autres secteurs
Economie totale	= Dette extérieure brute

Une fois l'allocation effectuée, les soustractions entre la dette totale et la dette extérieure ont été faites pour obtenir la répartition entre la dette extérieure et la dette intérieure. La procédure décrite précédemment a été appliquée pour tous les pays entre 2008 et 2020. Le Tableau 7.5 présente un exemple des résultats pour la France.

Tableau 7.5 | Répartition entre la dette extérieure et la dette intérieure pour la France (Source : calculs faits par l'auteur à partir des données QEDS et SCN)

SCN (MEUR)	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Economie totale	18 614 902 €	19 413 538 €	20 403 057 €	21 233 732 €	22 397 855 €	24 992 565 €
Sociétés non financières	3 919 905 €	4 138 952 €	4 369 400 €	4 599 423 €	4 673 869 €	4 980 231 €
Sociétés financières	10 287 913 €	10 754 409 €	11 347 267 €	11 840 395 €	12 711 067 €	14 463 208 €
Administration publique	2 910 169 €	2 993 718 €	3 062 829 €	3 123 152 €	3 252 319 €	3 701 898 €
Ménages et ISBLSM	1 496 915 €	1 526 457 €	1 623 562 €	1 670 763 €	1 730 502 €	1 847 227 €

Dette extérieure (**MEUR**)	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Economie totale	4 598 231 €	4 730 940 €	4 792 885 €	5 090 901 €	5 461 470 €	6 458 297 €
Sociétés non financières	495 791 €	530 623 €	549 981 €	495 790 €	511 248 €	550 185 €
Sociétés financières	2 773 083 €	2 885 626 €	2 976 393 €	3 334 494 €	3 599 720 €	4 306 249 €
Administration publique	1 329 357 €	1 314 691 €	1 266 511 €	1 260 618 €	1 350 503 €	1 601 863 €
Ménages et ISBLSM	- €	- €	- €	- €	- €	- €

Dette intérieure (**MEUR**)	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Economie totale	14 016 671 €	14 682 598 €	15 610 172 €	16 142 831 €	16 936 385 €	18 534 268 €
Sociétés non financières	3 424 114 €	3 608 329 €	3 819 419 €	4 103 633 €	4 162 621 €	4 430 046 €
Sociétés financières	7 514 830 €	7 868 783 €	8 370 874 €	8 505 901 €	9 111 347 €	10 156 959 €
Administration publique	1 580 812 €	1 679 027 €	1 796 318 €	1 862 534 €	1 901 816 €	2 100 035 €
Ménages et ISBLSM	1 496 915 €	1 526 457 €	1 623 562 €	1 670 763 €	1 730 502 €	1 847 227 €

La dernière étape de la collecte de données a consisté à obtenir la ventilation géographique de la dette extérieure entre les pays. L'objectif était de connaître les pays qui détiennent la dette extérieure d'un pays spécifique, ce qui est une information non divulguée principalement pour des raisons géopolitiques.

Afin d'estimer la ventilation géographique de la dette extérieure des pays, le CPIS a été utilisé comme référence principale car il présente les actifs d'investissement de portefeuille des émetteurs non-résidents, ventilés par pays. Le CPIS fournit des informations concernant les investissements de portefeuille sous forme de titres de créance, d'actions et de parts de fonds d'investissement. Comme le premier représente un instrument de dette, la ventilation géographique des titres de créance a été sélectionnée pour appliquer les proportions, comme le présente le Tableau 7.6.

Tableau 7.6 | Allocation de dette marginal inter-pays (Source : calculs faits par l'auteur à partir des données du CPIS)

2020	Investissement de:																				
Investissement en:	AU	BE	BR	CA	CN	FR	DE	IN	IE	IT	JP	LU	NL	PL	RU	ES	CH	GB	US	ROW	Total
AU		1%	0%	1%	5%	4%	6%	0%	3%	1%	20%	4%	1%	0%	0%	0%	2%	4%	20%	26%	100%

BE	0%		0%	0%	0%	18%	19%	0%	7%	4%	7%	8%	11%	0%	0%	1%	1%	2%	2%	18%	100%
BR	0%	0%		2%	0%	2%	2%	0%	4%	1%	3%	11%	4%	0%	0%	0%	2%	10%	19%	39%	100%
CA	2%	1%	0%		2%	2%	5%	0%	3%	0%	5%	4%	1%	0%	0%	0%	3%	4%	43%	24%	100%
CN	1%	0%	0%	0%	44%	1%	1%	0%	4%	0%	4%	6%	1%	0%	0%	0%	1%	2%	7%	26%	100%
FR	0%	3%	0%	0%	1%		15%	0%	8%	5%	9%	12%	7%	0%	0%	1%	2%	5%	8%	24%	100%
DE	1%	1%	0%	0%	1%	7%		0%	5%	3%	5%	10%	10%	0%	0%	1%	2%	5%	5%	42%	100%
IN	0%	0%	0%	2%	4%	1%	3%		2%	0%	6%	13%	1%	0%	0%	0%	1%	5%	18%	44%	100%
IE	0%	3%	0%	1%	0%	9%	12%	0%		4%	5%	8%	4%	0%	3%	2%	2%	12%	13%	23%	100%
IT	0%	2%	0%	0%	0%	17%	11%	0%	7%		7%	13%	1%	0%	0%	13%	1%	3%	4%	20%	100%
JP	2%	0%	0%	1%	5%	8%	2%	0%	4%	1%		5%	1%	0%	0%	1%	2%	6%	21%	42%	100%
LU	1%	5%	0%	1%	7%	21%	13%	0%	6%	3%	4%		3%	0%	2%	1%	5%	6%	9%	12%	100%
NL	1%	5%	0%	0%	1%	14%	17%	0%	6%	4%	6%	9%		0%	0%	3%	3%	4%	12%	16%	100%
PL	0%	4%	0%	2%	0%	8%	22%	0%	5%	3%	12%	8%	6%		0%	0%	3%	3%	7%	16%	100%
RU	0%	0%	0%	1%	0%	1%	5%	0%	25%	2%	2%	15%	4%	0%		0%	2%	7%	23%	14%	100%
ES	0%	2%	0%	0%	0%	18%	14%	0%	6%	13%	7%	8%	4%	0%	0%		1%	2%	5%	20%	100%
CH	1%	0%	0%	1%	1%	5%	4%	0%	11%	1%	4%	13%	3%	0%	0%	1%		9%	21%	23%	100%
GB	1%	1%	0%	1%	1%	7%	6%	0%	24%	1%	5%	11%	2%	0%	1%	1%	2%		18%	18%	100%
US	1%	0%	0%	3%	2%	3%	3%	0%	7%	1%	13%	7%	2%	0%	0%	0%	2%	5%		50%	100%
ROW	1%	1%	0%	1%	3%	6%	7%	0%	7%	2%	8%	8%	3%	0%	0%	1%	2%	4%	10%	33%	100%

Dans le tableau, les lignes représentent la partie du passif, le pays homologue étant représenté dans les colonnes. Par exemple, la lecture de la ligne « FR » et de la colonne « DE » signifie que l'Allemagne représente 15% du passif total de la France. La colonne « Reste du monde » (ROW) est la différence entre le total et la somme des 19 pays sélectionnés.

7.5 Méthode appliquée à une étude de cas : transcription de la méthode

Les effets de la pandémie de COVID-19 ont affecté l'activité économique mondiale de nombreuses manières. Pour cette raison, plusieurs mesures visant à aider à reconstruire les économies ont été mises en œuvre au niveau mondial. En Europe, l'Union européenne a lancé le budget à long terme de l'UE, qui est associé au programme NextGenerationEU (NGEU) axé sur la reconstruction de l'Europe après le COVID. En France, par exemple, le gouvernement a présenté en 2020 le plan de relance français, avec des fonds supplémentaires de 100 milliards d'euros pour soutenir l'activité économique et la création d'emplois. Le plan s'articule autour de trois piliers : transition écologique, compétitivité, cohésion sociale et territoriale, et un budget de 5,2 milliards d'euros est consacré à l'augmentation de l'efficacité énergétique du parc bâti résidentiel et tertiaire, notamment pour favoriser la rénovation thermique à l'échelle nationale.

Selon le rapport détaillé du Congrès national français, le budget du plan de relance français sera utilisé de la manière suivante :

- 2,0 milliards d'euros d'aides financières pour l'achat d'équipements de chauffage et d'eau chaude sanitaire performants et de matériaux isolants pour les bâtiments résidentiels (principalement via MaPrimeRénov')
- 0,2 milliard d'euros pour les entreprises privées
- 3,2 milliards d'euros d'investissements dans des mesures de rénovation thermique dans les bâtiments publics (écoles, hôpitaux, logements sociaux, etc.)

L'objectif de l'étude de cas est donc d'évaluer les impacts environnementaux et économiques associés au plan de relance français, en particulier les incitations (aides financières) à la réalisation d'une rénovation thermique massive dans les bâtiments publics et résidentiels. L'unité fonctionnelle est de mener une rénovation massive en France favorisée par les incitations fiscales : 2 milliards d'euros pour les bâtiments résidentiels et 3,2 milliards d'euros pour les bâtiments publics.

Ce budget est l'argent injecté dans l'économie française, en provenance de l'étranger, destiné à financer le plan de relance. Cet argent est utilisé pour acheter des équipements de chauffage et d'eau chaude sanitaire performants et des matériaux isolants. Dans un premier moment, les ménages (MS) et l'Administration Publique (AP) réalise des travaux de rénovation pour, dans un deuxième moment, réduire leur consommation d'énergie. Ce dernier est considéré comme une perturbation exogène dans les périodes qui suivent les travaux de rénovation, comme montre la Figure 7.6.

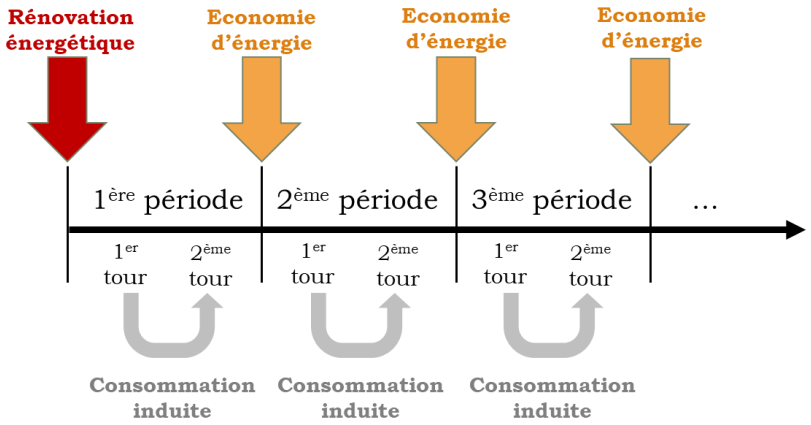


Figure 7.6 | Etude de cas (Source : produit par l'auteur)

Il n'existe aucune information sur les types de rénovations thermiques qui sont spécifiquement financées par le plan. Pour cette raison, trois options ont été considérées dans cette thèse : une **perturbation simplifiée de la totalité du budget consacré à la rénovation de bâtiments publiques et résidentiels**, une **perturbation détaillée et une perturbation simplifiée du budget consacré à la rénovation de bâtiments résidentiels**, comme montre le Tableau 7.7.

Tableau 7.7 | Versions de la perturbation exogène pour les travaux de rénovation énergétique (Source : hypothèses de l'auteur)

	Perturbation simplifiée, budget total	**Perturbation détaillée, uniquement résidentiel**	**Perturbation simplifiée, uniquement résidentiel**
Périmètre	Bâtiments résidentiels et publiques	Bâtiments résidentiels	Bâtiments résidentiels
Activités affectés (premier plan)	« Travaux de construction » (activité « construction works (45)» sur la liste de produits et services couverts par EXIOBASE)	Activités marginales, définies par le modèle MENFIS[24]	« Travaux de construction » (activité « construction works (45)» sur la liste de produits et services couverts par EXIOBASE)

7.5.1 Quantification des perturbations exogènes simplifiée et détaillée

7.5.1.1 Version simplifiée, budget total

Dans la version simplifiée, le vecteur de perturbation initial est donc de 5,2 milliards d'euros dans la ligne française « travaux de construction » et de zéro pour toutes les autres activités. Cette perturbation exogène initiale intervient au début de la première période (représentée par la flèche rouge dans la Figure 7.6). Les 5,2 milliards d'euros proviennent de l'Administration Publique (AP) (3,2 milliards d'euros) et des ménages (MS) (2,0 milliards d'euros).

Toutefois, les ménages sont désagrégées en trois groupes selon leur niveau de revenu. Par conséquent, puisque la perturbation doit être cohérente avec les flux de stocks, elle doit également être désagrégée. La désagrégation des travaux de rénovation faits par le ménages s'applique aussi à la perturbation détaillée.

Le principal outil du plan de relance pour encourager les travaux de rénovation thermique dans les bâtiments résidentiels est l'augmentation de la portée des primes MaPrimeRénov' (MPR). Il convient de mentionner que MPR a été lancée en 2020 et qu'elle était limitée uniquement aux groupes à faibles revenus. Une façon de comprendre l'évolution marginale du nombre de travaux de rénovation thermique pour le niveau de revenu de chaque ménage est d'étudier l'évolution des valeurs MPR des primes en 2020 et 2021, sachant que le plan de relance a permis d'étendre le champ d'application de la MPR aux niveaux de revenus moyens et élevés. Ces deux catégories de revenus étaient auparavant couvertes par la mesure de crédit d'impôt appelée CITE (pour Crédit d'Impôt pour la Transformation Energétique),

[24] Modèle ENergie FIScalité des logements (Nauleau and Saussay, 2019)

qui s'est éteinte depuis la création de MPR. Le tableau comparant les aides financières avant et après le plan de relance est présenté en annexe (Appendix 5).

Les estimations sont les suivantes : 24 % pour les ménages faiblement qualifiés, 58 % pour les ménages moyennement qualifiés et 18 % pour les ménages hautement qualifiés, donc la perturbation de 2 milliards est divisée en : 0,474 milliard d'euros pour/par les MS-FQ, 1,169 milliard d'euros pour/par les MS-MQ et 0,357 milliard d'euros pour/par les MS-HQ.

Les perturbations exogènes qui se produisent au début des autres périodes sont l'énergie économisée (flèches orange dans la Figure 7.6) et l'argent dépensé à nouveau à partir de la distribution monétaire (flèches grises dans la Figure 7.6).

L'énergie économisée dans cette version simplifiée est estimée à partir de la littérature. Pour cela, trois options sont décrites ici : (A) faire varier le temps de retour sur investissement de 10 à 30 ans, une pratique courante sur les études d'efficacité énergétique ; (B) utiliser les enquêtes sur l'argent économisé après la réalisation de travaux de rénovation thermique dans leur logement, présentées en termes de retour sur investissement par Blaise & Glachant (2019) ; et (C) utiliser l'estimation faite par le Gouvernement de 139 GWh d'énergie primaire économisée pour 989 millions d'euros investis dans la rénovation thermique des bâtiments des administrations publiques (140,5 GWh/milliard d'euros).

La quantification de l'énergie économisé est donc obtenue en fonction de l'investissement sur les travaux dans cette version simplifiée. Les sources d'énergie affectées sont obtenues à partir de statistiques sur les consommations pour le chauffage des bâtiments résidentiels et tertiaires faits par le Centre d'études et de recherches économiques sur l'énergie (CEREN, 2021a, 2021b). Ces données ont été combinées avec les prix moyens de chaque source d'énergie, à partir de diverses études de l'Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME), du service des données et études statistiques (SDES), de l'Association de l'observatoire des réseaux de chaleur et de froid (AMORCE) (ADEME 2020; SDES 2020; AMORCE 2020). Les réductions de consommation d'énergie par source, pour les trois options, sont présentées dans le Tableau 7.8.

Tableau 7.8 | Perturbation concernant les économies d'énergie de la deuxième période et ainsi de suite, version simplifiée (MEUR) (Source : calculs de l'auteur à partir de données du CEREN, SDES, AMORCE, ADEME)

Source d'énergie	Activité sur EXIOBASE	Option A	Option B	Option C
Chaleur urbain	Steam and hot water supply services	-13.7	-3.5	-3.3
Diesel	Gas/Diesel Oil	-24.5	-6.2	-6.5
Gaz naturel	Distribution services of gaseous fuels through mains	-67.8	-17.1	-18.6
Gaz de pétrole liquéfié	Liquefied Petroleum Gases (LPG)	-4.8	-1.2	-1.2
Granulés de bois	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	-13.3	-3.4	-4.7
Electricité	Total electricity	-49.2	-12.4	-13.2
	Electricity by coal	-2.8	-0.7	-0.7
	Electricity by gas	-3.1	-0.8	-0.8
	Electricity by nuclear	-37.2	-9.4	-10.0
	Electricity by hydro	-4.3	-1.1	-1.2
	Electricity by wind	0.0	0.0	0.0
	Electricity by petroleum and other oil derivatives	-0.5	-0.1	-0.1
	Electricity by biomass and waste	-0.8	-0.2	-0.2
	Electricity by solar photovoltaic	0.0	0.0	0.0
	Electricity by solar thermal	0.0	0.0	0.0
	Electricity by tide, wave, ocean	0.0	0.0	0.0
	Electricity by Geothermal	0.0	0.0	0.0
	Electricity n.e.c.	-0.5	-0.1	-0.1
	Transmission services of electricity	-7.5	-1.9	-2.0
	Distribution and trade services of electricity	-28.6	-7.2	-7.7

Comme l'option C présente des valeurs intermédiaires par rapport aux deux autres options, elle est le scénario retenu.

7.5.1.2 Version détaillée, uniquement résidentiel

Les aides financières pour la rénovation des bâtiments résidentiels sont principalement accordées par le biais des dispositions MaPrimeRénov. Le plan de relance français a permis d'augmenter les subventions pour l'achat d'équipements spécifiques et pour la pose d'isolants (panneaux, fenêtres), mais le plus grand changement a été d'ouvrir les subventions à tous les ménages, quel que soit leur niveau de revenu.

Considérant que MENFIS prend également en compte d'autres aides qui interviendraient sans lien avec le plan de relance et influenceraient le nombre de travaux de rénovation ainsi que d'autres résultats du modèle, deux simulations ont été réalisées pour 2021, sachant que l'année de référence est 2020. La première consistait à obtenir un scénario « business-as-usual » (BAU), c'est-à-dire à exécuter le modèle sans les changements déclenchés par le plan de relance. La seconde simulation a été réalisée en augmentant les subventions MaPrimeRénov' aux nouvelles valeurs facilitées par le plan de relance pour obtenir une

augmentation de 2 milliards d'euros de travaux de rénovation thermique. Les résultats par geste de rénovation sont présentés dans le Tableau 7.9.

Tableau 7.9 | Résultats des simulations MENFIS (Source : Simulations réalisées par le CSTB)

Geste de rénovation	Coût (€/travaux)	BAU (nombre de travaux)	MPR (nombre de travaux)	Only recovery Plan (nombre de travaux)
Chaudière à condensation gaz	4343	215 029	240 599	25 570
Chaudière à condensation fioul	4343	145 496	212 149	66 653
PAC air-air	7934	199 981	299 117	99 136
Chaudière bois (MI) ou chauffage urbain (LC)	16513	42 036	41 922	- 114
Insert bois en appoint	4638	288 608	477 204	188 596
PAC air / eau	10913	29 814	31 195	1 381
Isolation des fenêtres	7541	683 296	726 961	43 665
Isolation des murs	9877	424 205	697 056	272 851
Isolation des combles ou toitures	5064	428 935	658 933	229 998

Les gestes de rénovation listés dans le tableau ont été modélisés à partir des activités disponibles sur EXIOBASE. Les liens entre les gestes et les activités EXIOBASE sont présentés dans le Tableau 7.10.

Tableau 7.10 | Relation entre le geste de rénovation et les activités d'EXIOBASE (Source : Hypothèses faites par l'auteur)

Retrofitting work	EXIOBASE **activity**
Chaudière à condensation gaz	Machinery and equipment n.e.c.
Chaudière à condensation fioul	Machinery and equipment n.e.c.
PAC air-air	Machinery and equipment n.e.c.
Chaudière bois (MI) ou chauffage urbain (LC)	Machinery and equipment n.e.c.
Insert bois en appoint	Machinery and equipment n.e.c.
PAC air / eau	Machinery and equipment n.e.c.
Isolation des fenêtres	Glazing - Glass and glass products Frame - Aluminium and aluminium products Rubber and plastic products Wood and products of wood and cork (except furniture)
Isolation des murs	Glass and glass products Manufacture of other non-metallic mineral products n.e.c. Rubber and plastic products Wood and products of wood and cork (except furniture)
Isolation des combles ou toitures	Glass and glass products Manufacture of other non-metallic mineral products n.e.c. Rubber and plastic products Wood and products of wood and cork (except furniture)

Pour quantifier en termes monétaires combien chaque activité est affectée (définition de la perturbation exogène), les coûts présentés dans le Tableau 7.9 ont été utilisés. Les isolants et les fenêtres présentent plus d'une activité EXIOBASE, pour faire la répartition entre chaque activité, des études statistiques sue les parts de marché ont été utilisés. Pour les fenêtres, l'étude de l'Union des Fabricants de Menuiseries a été utilisé (UFME, 2020) **et pour les isolants, une étude confidentielle réalisée par le CSTB a été utilisée**. La perturbation est présentée dans le Tableau 7.11

Tableau 7.11 | Perturbation exogène pour la première période (Source : Calculs faits par l'auteur à partir de simulations MENFIS, données statistiques de l'UFME et CSTB)

Activité EXIOBASE	Chaudière à condensation gaz	Chaudière à condensation fioul	PAC air-air	Chaudière bois (MI) ou chauffage urbain (LC)	Insert bois en appoint	PAC air / eau	Isolation des fenêtres	Isolation des murs	Isolation des combles ou toitures	Total (milliard d'euros)
Machinery and equipment n.e.c.	0,111	0,289	0,787	-0,002	0,875	0,015	-	-	-	***2,075***
Glass and glass products	-	-	-	-	-	-	0,238	0,839	0,363	***1,440***
Aluminium and aluminium products	-	-	-	-	-	-	0,032	-	-	***0,032***
Rubber and plastic products	-	-	-	-	-	-	0,030	1,270	0,549	***1,850***
Wood and products of wood and cork (except furniture)	-	-	-	-	-	-	0,029	0,117	0,051	***0,197***
Manufacture of other non-metallic mineral products n.e.c.	-	-	-	-	-	-	-	0,468	0,202	***0,670***
Total	***0,111***	***0,289***	***0,787***	***-0,002***	***0,875***	***0,015***	***0,329***	***2,695***	***1,165***	***6,264***

Le Tableau 7.11 montre que les ménages ont dépensé 6,264 milliard d'euros en travaux de rénovation. Comme pour la version simplifiée, il faut désagréger la dépense des ménages par chaque groupe (MS-FQ, MS-MQ et MS-HQ). MENFIS fournit les montants des travaux de rénovation thermique effectués par les ménages, par quintile de revenu. Le rapport entre la répartition par quintile de revenue et les niveaux de revenue par qualification (de l'OIT) a été fait à partir des données de répartition de la population française par catégorie socio-économique de l'Institut National de Statistiques et Etudes Economiques (INSEE, 2018).

Pour l'économie d'énergie, MENFIS fournit la quantité d'énergie économisé en conséquence des travaux de rénovation réalisés, par vecteur énergétique, comme présenté dans le Tableau 7.12. Les simulations de MENFIS montrent l'économie d'énergie en termes physiques. Pour faire l'équivalent monétaire, les coûts utilisés dans la version simplifié ont été appliqués, comme présenté dans la dernière colonne du Tableau 7.12.

Tableau 7.12 | Economie d'énergie simulé par MENFIS (Source : Calculs faits par l'auteur à partir de simulations MENFIS, données statistiques de l'ADEME,AMORCE et SDDS)

Vecteur énergétique	Activité EXIOBASE	Energie économisée (TWh)	Energie économisée (milliard d'euros)
Chaleur urbain	Steam and hot water supply services	-0.1	-11.1
Diesel	Gas/Diesel Oil	-1.3	-66.6
Gaz naturel	Distribution services of gaseous fuels through mains	-0.9	-34.4
Gaz de pétrole liquéfié	Liquefied Petroleum Gases (LPG)		0.0
Granulés de bois	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	0.8	51.0
Electricité	Total electricity	-0.1	-14.9
	Electricity by coal	-	-0.8
	Electricity by gas	-	-0.9
	Electricity by nuclear	-	-11.3
	Electricity by hydro	-	-1.3
	Electricity by wind	-	0.0
	Electricity by petroleum and other oil derivatives	-	-0.2
	Electricity by biomass and waste	-	-0.2
	Electricity by solar photovoltaic	-	0.0
	Electricity by solar thermal	-	0.0
	Electricity by tide. wave. Ocean	-	0.0
	Electricity by Geothermal	-	0.0
	Electricity n.e.c.	-	-0.2
	Transmission services of electricity	-	-2.3
	Distribution and trade services of electricity	-	-8.7

7.5.1.3 Version simplifiée, uniquement résidentiel

La perturbation exogène a la même ampleur que la version détaillée, c'est-à-dire 5,8 milliards d'euros. L'hypothèse est que l'argent reçu par les ménages pour effectuer des services de rénovation thermique ne couvre pas la totalité de leurs dépenses. Les ménages peu qualifiés reçoivent 24%, les ménages moyennement qualifiés 58% et les ménages hautement qualifiés 18% du budget total pour les bâtiments résidentiels. Dans cette version, ces proportions restent les mêmes, c'est-à-dire que les ménages peu qualifiés dépensent 1,4 milliard d'euros, les ménages moyennement qualifiés 3,4 milliards d'euros et les ménages hautement qualifiés 1,0 milliard d'euros dans l'activité d'Exiobase appelée « travaux de construction », comme dans la version simplifiée du budget total.

Pour les économies d'énergie, les hypothèses sont les mêmes que celles présentées pour la version simplifiée du budget total. L'option retenue pour estimer les économies d'énergie en fonction de l'argent investi est que 140,5 GWh d'énergie primaire sont économisés par milliard d'euros investi dans les travaux de rénovation thermique. Cela signifie que, pour 5,8

milliards, 816 GWh sont économisés en énergie primaire, ou 752 GWh en énergie finale. Il en résulte une économie d'environ 0,070 milliard d'euros par an pour les ménages.

7.5.2 Définition des transactions et des secteurs institutionnels pertinents

Dans les versions simplifiée et détaillée, les dépenses totales utilisées pour l'achat d'équipements efficaces et de matériaux isolants sont comptabilisées comme une utilisation de la « formation brute de capital fixe » pour les ménages (MS), par niveau de revenu (faiblement qualifiés - FQ, moyennement qualifiés – MQ, hautement qualifiés –HQ) et pour les administrations publiques (AP) et, en contrepartie, elles constituent une ressource pour les sociétés non financières (SNF). Cet argent supplémentaire provient d'une part de l'Union Européenne (40 %), comptabilisée comme « autres transactions courantes » et l'autre partie provient des emprunts contractés par le gouvernement français, provenant d'autres secteurs institutionnels, comme on peut l'obtenir dans la base de données des stocks.

Les AP sont divisées en deux fonctions : les affaires sociales (AP-AS) et le plan de relance (AP-RP). Cette séparation permet une meilleure traçabilité des flux et des stocks liés au plan de relance et des autres affaires indépendantes du plan. Par conséquent, les secteurs institutionnels qui sont inclus sont les AP, SNF, SF, MS-FQ, MS-MQ, MS-HQ, et ROW.

7.5.3 Distribution monétaire et cohérence entre stock et flux

La distribution monétaire de l'étude de cas a été codée en python, où les équations présentées dans la Section 7.4.2.3 ont été appliquées. Les variations des composantes de la valeur ajoutée sont comptabilisées dans la feuille Excel avec la MFT qui enregistre toutes les transactions. Les équations permettant d'obtenir les paramètres du Tableau 7.3 sont présentées ci-dessous. Pour l'excédent d'exploitation, les SNF paient le montant total reçu par chaque secteur institutionnel (k), comme présenté dans l'équation 7-7.

$$OS^R{}_k = \gamma_k \cdot OS^U{}_{NFC} \qquad \text{Equation 7-7}$$

Le paramètre "γ" représente les proportions de redistribution de la valeur ajoutée brute à chaque secteur institutionnel (k). Bien entendu, la somme des excédents d'exploitation reçus par chaque secteur institutionnel est égale au montant payé par les SNF, ou, la somme des γ_k est égale à 1.

Les composantes de la valeur ajoutée de l'EXIOBASE comprennent les salaires, les traitements et les cotisations sociales des employeurs, qui représentent les dépenses brutes des employeurs en matière de travail. Ces composantes sont normalement désagrégées en salaires

et traitements (représentés par la transaction D11 du SCN) et en cotisations sociales patronales (représentées par la transaction D12 du SCN). Dans cette thèse, la désagrégation a été faite pour distinguer les cotisations sociales de l'employeur, qui ne sont pas une ressource pour les ménages, mais pour le gouvernement, des cotisations sociales de l'employé, qui sont payées en fonction de leur revenu. Pour désagréger la composante valeur ajoutée d' EXIOBASE concernant les salaires, traitements et cotisations sociales patronales (G_{wse}), on utilise les valeurs des bilans de l'économie française du SCN (Appendix 3).

$$ESC^U{}_{NFC} = \frac{D12}{D11+D12} \cdot G_{wse} \qquad \text{Equation 7-8}$$

$$W^R{}_{HH,i} = \frac{D11}{D11+D12} \cdot G_{wse,i} \text{ (i = FQ,MQ,HQ)} \qquad \text{Equation 7-9}$$

Les ménages paient des impôts sur le revenu (TI) et des cotisations sociales (SC) au gouvernement, proportionnellement à leurs variations de revenu (θ et ρ), comme présenté dans les Équations 7-10 et 7-11.

$$TI^U{}_i = \theta \cdot (W^R{}_i + OS^R{}_i) \qquad \text{Equation 7-10}$$

$$SC^U{}_i = \rho \cdot W^R{}_i \qquad \text{Equation 7-11}$$

Où $\theta = \frac{D5}{D11+B2G}$, et $\rho = \frac{D61-D12}{D11}$

Les deux taux (θ et ρ) sont obtenus à partir des soldes des transactions non financières pour la France issus du SCN (Appendix 3). Le taux pour les impôts sur le revenu (θ) est obtenu en divisant le montant de « D5 - impôts courants sur le revenu et le patrimoine » payé par les ménages par le revenu total, qui est composé des salaires et traitements (D11) et de l'excédent d'exploitation (B2G). En ce qui concerne les cotisations sociales, dans le SCN, les cotisations sociales de l'employeur (D12) sont totalement perçues par les ménages, qui sont chargés de payer l'État par le biais des cotisations sociales des employés (D61).

Le Tableau 7.13 présente pour mémoire la description des six scénarios évalués dans la thèse. Les MFT sont présentées dans les sections suivantes pour le premier tour de la première période analysée, pour les scenarios Sc1.a, Sc2.a et Sc3.a.

Tableau 7.13 | Description des scénarios

Budget total	Uniquement résidentiel		Description des scénarios
Simplifié	**Détaillé**	**Simplifié**	
Sc1.a	**Sc2.a**	**Sc3.a**	L'excédent d'exploitation est versé à chaque groupe de revenus selon les proportions de la rémunération des employés.
Sc1.b	**Sc2.b**	**Sc3.b**	L'excédent d'exploitation total est perçu par les ménages hautement qualifiés
Sc1.c	**Sc2.c**	**Sc3.c**	L'excédent d'exploitation total est épargné par les ménages sous sa forme agrégée.

7.5.3.1. Scenario Sc1.a

Le Tableau 7.14 présente la MFT pour le premier tour de distribution de la première période, pour le scenario Sc1.a. Les valeurs surlignées en rouge représentent la perturbation. L'AP-PR dépense 3,2 milliards d'euros en formation brute de capital fixe et 2,0 milliards d'euros en prestations sociales, telles que MPR aux ménages. Cet argent provient à 40 % de l'Union européenne, et à 60 % d'emprunts contractés comme d'habitude par le gouvernement pour financer les politiques nationales. Les actions des émetteurs d'emprunts sont tirées de la «base de données des stocks », telle que présentée dans la Section 7.4.4.

Tableau 7.14 | Matrice de flux de transactions, premier tour de la première période, Sc1.a (Source : Calculs de l'auteur à partir des équations développées dans la thèse)

(Milliard d'euros)	SNF		SF		AP-PR		AP-AS		MS						ROW		Σ
									FQ		MQ		HQ				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Dépenses de consommation finale																	0
Formation brute de capital		5.20			3.20				0.47		1.17		0.36				0
Exportations de biens et de services		0.02													0.02		0
Importations de biens et de services	1.11															1.11	0
Excédent d'exploitation	1.25	0.71		0.05				0.24		0.01		0.15		0.09	0.44	0.44	0
Salaires et rémunérations	1.89									0.08		1.10		0.71			0
Cotisations sociales de l'employeur	0.63							0.63									0
Impôts sur les produits	0.20							0.20							0.09	0.09	0
Autres impôts sur la production	0.15							0.15							0.03	0.03	0
Intérêts																	0
Impôts actuels sur le revenu, le patrimoine, etc.								0.46	0.02		0.27		0.17				0
Cotisations sociales								0.30	0.01		0.17		0.11				0
Prestations sociales					2.00					0.47		1.17		0.36			0
Autres transactions						2.08									2.08		0
Position nette non financière		0.71		0.05		-3.12		1.98		0.06		0.80		0.51		-1.00	0
Dépôts	0.44			0.28			0.99		0.06		0.80		0.51		-2.52		0
Dette	0.27		0.33			3.12	1.00								1.52		0
Position nette non financière		-0.71		-0.05		3.12		-1.98		-0.06		-0.80		-0.51		1.00	0

Use: uses, Res: ressources

L'AP-AS prête 1,0 milliard d'euros à l'AP-PR, ce qui peut s'expliquer par les différents niveaux d'organisation (municipal, régional et national) du gouvernement. Le montant de 1,52 milliard d'euros provient du ROW, et les pays qui prêtent de l'argent (émetteurs de prêts) sont tirés de la matrice transnationale de qui à qui, également issue de la « base de données des stocks ».

Les SNF reçoivent, par le biais du secteur de la construction, 5,2 milliards d'euros, utilisés pour payer les salaires et traitements (2,52 milliards d'euros), les impôts sur les produits (0,20 milliard d'euros), les autres impôts sur la production (0,15 milliard d'euros) et l'excédent d'exploitation (1,25 milliard d'euros). La variation des exportations est de 0,02 milliard d'euros, tandis que la variation des importations est de 1,11 milliard d'euros. La perturbation a été appliquée aux activités de travaux de construction qui, selon les données d'EXIOBASE, importent 13% de leurs ressources.

À la fin du premier tour de la première période, les SNF sont en position de prêt net, avec 0,71 milliard d'euros qui vont en tant qu'actif financier sur le compte « dépôts ». L'argent prêté à l'AP-PR (0,3 milliard d'euros) est retiré de leur compte « dépôts », ce qui donne 0,4 milliard d'euros à déposer aux CF. Par conséquent, la position financière est la somme des

deux actifs financiers : 0,4 milliard d'euros en numéraire et en dépôts plus les 0,3 milliard d'euros en prêts, ce qui correspond à la position créditrice nette non financière.

Les CF servent d'intermédiaires dans les transactions financières, recevant le total des dépôts des autres secteurs institutionnels et versant les prêts aux agents qui ont besoin d'emprunter l'argent.

Les trois groupes de ménages sont en position de prêt net. Les MS-FQ ont la plus faible augmentation (0,06 milliard d'euros), tandis que les MS-MQ ont la plus forte augmentation (0,80 milliard d'euros), suivis par les MS-HQ (0,51 milliard d'euros). Ces variations nettes positives des transactions non financières entraînent une augmentation des actifs financiers, par le biais des dépôts auprès des SF. Cependant, l'augmentation observée des dépôts n'est que temporaire car une partie de l'argent reçu par les ménages est dépensée dans un second tour de la même période.

7.5.3.2. Scenario Sc2.a

Les aides financières provenant du plan de relance ne couvrent qu'une partie de l'argent dépensé dans les travaux de rénovation. La version détaillée de la perturbation économique permet de modéliser l'argent réellement dépensé par les ménages car MENFIS simule l'augmentation de l'aide financière du MPR en fournissant comme résultat le nombre de travaux de rénovation induits par cette augmentation et les coûts pour chaque travail. Selon les simulations MENFIS, une augmentation de 2,00 milliards d'euros du MPR entraîne une augmentation de 5,80 milliards d'euros de l'argent dépensé dans les travaux de rénovation, c'est-à-dire qu'environ deux tiers de l'argent dépensé dans la rénovation sont financés par d'autres aides ou proviennent de l'argent économisé par les ménages.

La source d'argent pour payer les travaux de rénovation thermique (comptabilisée comme formation brute totale de capital fixe) est un élément important pour construire une MFT. Ici, l'hypothèse est que les ménages contractent des prêts à taux zéro pour financer la partie restante de leurs travaux de rénovation, ce qui est l'aide financière la plus souvent adoptée lorsqu'elle est combinée avec MPR pour la simplicité de leur jonction dans les procédures bancaires . Tableau 7.15 présente la MFT pour le scenario Sc2.a.

Tableau 7.15 | Matrice de flux de transactions, premier tour de la première période, Sc2.a (Source : Calculs de l'auteur à partir des équations développées dans la thèse)

(Milliard d'euros)	SNF		SF		AP-PR		AP-AS		MS						ROW		Σ
									FQ		MQ		HQ				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Dépenses de consommation finale																	0
Formation brute de capital		5,80							0,71		3,40		1,68				0
Exportations de biens et de services		0,03													0,03		0
Importations de biens et de services	1,32															1,32	0
Excédent d'exploitation	1,26	0,72		0,05				0,24		0,01		0,11		0,12	0,53	0,53	0
Salaires et rémunérations	2,10									0,08		0,96		1,06			0
Cotisations sociales de l'employeur	0,71							0,71									0
Impôts sur les produits	0,24							0,24							0,10	0,10	0
Autres impôts sur la production	0,20							0,20							0,03	0,03	0
Intérêts																	0
Impôts actuels sur le revenu, le patrimoine, etc.								0,51	0,02		0,23		0,26				0
Cotisations sociales								0,33	0,01		0,15		0,17				0
Prestations sociales					2,00					0,47		1,17		0,36			0
Autres transactions						0,80									0,80		0
Position nette non financière		0,72		0,05		-1,20		2,23		-0,18		-1,54		-0,57		0,50	0
Dépôts	0,61			3,88			1,85		0,06		0,69		0,76		-0,09		0
Dette	0,10		3,93			1,20	0,38			0,24		2,24		1,33	0,58		0
Position nette non financière		-0,72		-0,05		1,20		-2,23		0,18		1,54		0,57		-0,50	0

Les MS-FQ dépensent 0,82 milliard d'euros en travaux de rénovation, 0,47 milliard d'euros provenant des primes RMP et 0,35 milliard d'euros de prêts à taux zéro. Dans le processus de distribution monétaire, 0,13 milliard d'euros reviennent aux MS-FQ, dont ils dépensent 0,03 milliard d'euros en impôts et cotisations sociales. Ainsi, à la fin de ce premier tour, ils sont en position d'emprunteur net, comme prévu, puisqu'ils ont contracté des prêts (prêts à taux zéro) pour financer leurs travaux de rénovation. Cependant, elles transfèrent 0,10 milliard d'euros sous forme de dépôts temporaires aux SF, ce qui induit une consommation au second tour. Cela se produit également pour les deux autres groupes de revenus, les MS-MQ transfèrent 1,20 milliard d'euros sous forme de dépôts temporaires aux SF et les MS-HQ transfèrent 1,31 milliard d'euros aux SF. L'argent total qui déclenche la consommation induite est de 2,61 milliards d'euros, qui seront en partie épargnés et en partie dépensés en biens et services de consommation.

Les SNF reçoivent 6,26 milliards d'euros et redistribuent la plus grande partie de l'argent reçu aux SF, aux MS, aux AP et au ROW. Comme dans les scénarios précédents, leur position créditrice nette correspond à l'excédent qu'ils reçoivent, qui est ici de 0,77 milliard d'euros.

L'AP-PR est l'autre secteur institutionnel en position d'emprunteur net car il contracte des prêts de 1,2 milliard d'euros pour financer le plan de relance.

7.5.3.3. Scenario Sc3.a

La version simplifiée de la perturbation ne prenant en compte que la construction résidentielle consiste en 5,80 milliards de dépenses, payées par les ménages aux sociétés non financières, où le seul produit affecté au premier plan est les « travaux de construction ». La MFT pour le scénario Sc3.a, où l'excédent d'exploitation est distribué à chaque groupe de revenus dans les mêmes proportions que les salaires et traitements, est présenté dans le Tableau 7.16.

Tableau 7.16 | Matrice de flux de transactions, premier tour de la première période, Sc3.a (Source : Calculs de l'auteur à partir des équations développées dans la thèse)

(Milliard d'euros)	SNF		SF		AP-PR		AP-AS		MS						ROW		Σ
									FQ		MQ		HQ				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Dépenses de consommation finale																	0
Formation brute de capital		5,80							1,38		3,39		1,04				0
Exportations de biens et de services		0,03													0,03		0
Importations de biens et de services	1,23															1,23	0
Excédent d'exploitation	1,39	0,79		0,06				0,27		0,01		0,17		0,10	0,49	0,49	0
Salaires et rémunérations	2,10									0,09		1,22		0,79			0
Cotisations sociales de l'employeur	0,71							0,71									0
Impôts sur les produits	0,23							0,23							0,10	0,10	0
Autres impôts sur la production	0,16							0,16							0,03	0,03	0
Intérêts																	0
Impôts actuels sur le revenu, le patrimoine, etc.								0,52	0,02		0,30		0,19				0
Cotisations sociales								0,33	0,01		0,19		0,13				0
Prestations sociales					2,00					0,47		1,17		0,36			0
Autres transactions						0,80									0,80		0
Position nette non financière		0,79		0,06		-1,20		2,21		-0,84		-1,33		-0,11		0,41	0
Dépôts	0,69			3,87			1,83		0,06		0,89		0,57		-0,18		0
Dette	0,10		3,93			1,20	0,38			0,90		2,22		0,68	0,58		0
Position nette non financière		-0,79		-0,06		1,20		-2,21		0,84		1,33		0,11		-0,41	0

Il existe deux différences principales par rapport à la version détaillée. La première concerne le montant que chaque groupe de revenu dépense pour les services de rénovation thermique. Dans cette version, les ménages peu qualifiés doublent leurs dépenses par rapport à la version détaillée, tandis que les ménages très qualifiés réduisent de 40% les sommes consacrées à la formation de capital. Les ménages moyennement qualifiés ne modifient pas leurs dépenses. La deuxième différence réside dans les proportions des composantes de la valeur ajoutée. Dans cette version, l'excédent d'exploitation est plus élevé que dans la version détaillée, tandis que les impôts sont plus faibles. Par conséquent, les ressources des administrations publiques sont plus faibles que dans la version précédente, alors que les

ménages ont un revenu plus élevé dans cette version. Ces différences sont également vraies pour les scénarios Sc3.b et Sc3.c.

7.5.4 Redistribution monétaire et cohérence stock-flux

Le deuxième tour de redistribution monétaire se produit lorsque l'argent instantanément cumulé au premier tour est dépensé en biens et services de consommation. Deux défis majeurs se posent lors de la mise en relation des deux premiers tours : identifier combien d'argent cumulé au premier tour est dépensé au second tour (facteur α pour chaque groupe de revenu) et identifier comment l'argent est dépensé ($\mathcal{C}$, matrice des modèles de consommation marginale).

Considérant que les données d'EXIOBASE fournissent la consommation des ménages agrégés en tant que secteur institutionnel, une désagrégation est nécessaire en termes des trois groupes de revenus. Dans l'étude de cas, les hypothèses sont les mêmes pour les deux approches (simplifiée et détaillée). En 2018, l'INSEE a posé aux ménages français la question suivante : « Si votre revenu augmentait, comment dépenseriez-vous cet argent supplémentaire ? » (Lelièvre & Remila, 2018a). Leurs résultats sont présentés par tranche de revenus des ménages, répartis en quatre catégories : bas revenus, revenus modestes, classes moyennes et riches. Leur classification est basée sur le niveau de pauvreté défini par la Direction de la recherche, des études, de l'évaluation et des statistiques. La classification des bas revenus concerne les ménages ayant un revenu inférieur au seuil de pauvreté, les bas revenus correspondent aux ménages qui perçoivent plus que le seuil de pauvreté et moins que le seuil du quatrième décile. Les ménages de classe moyenne ont un revenu supérieur au seuil du quatrième décile et inférieur au troisième quartile, et les ménages aisés correspondent au groupe ayant un revenu supérieur au seuil du troisième quartile (Lelièvre & Remila, 2018b, encadré 1). La correspondance entre cette classification et celle de l'OIT a été faite comme montre la Figure 7.7.

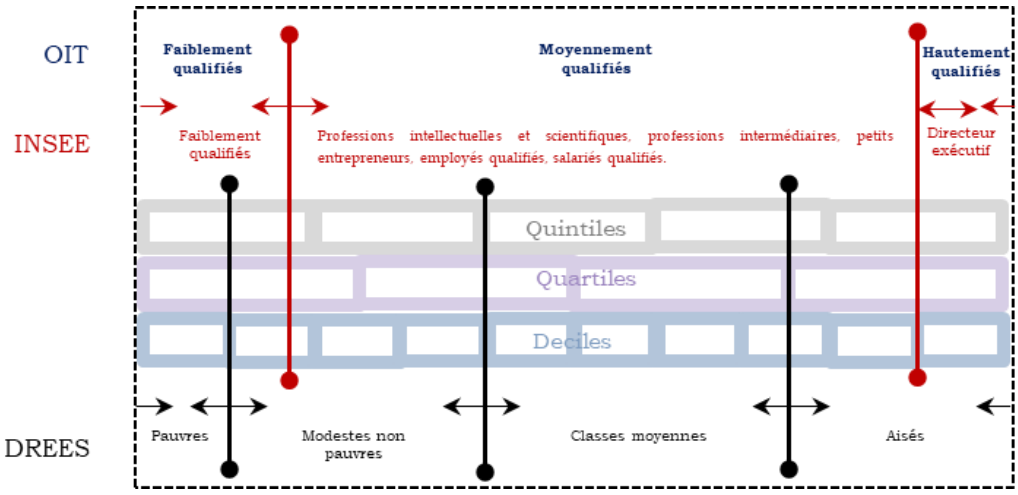


Figure 7.7 | Corrrespondance entre les divers classifications socio-économiques (Source : Compilation faite par l'auteur à partir des données de l'INSEE, de l'OIT et de DREES)

Ces liens sont établis dans le but d'identifier ce que chaque groupe de revenu fait avec l'argent supplémentaire reçu, ou, les modèles de consommation marginale. Le Tableau 7.17 présente les résultats par catégorie de biens et services de consommation, qui doivent être associés aux activités d'EXIOBASE.

Tableau 7.17 | Répartition des dépenses d'une augmentation hypothétique du revenu, par groupe de revenu (Source : compilation de l'auteur à partir de l'enquête DREES)

Catégorie de biens et services de consommation	Faiblement qualifiés	Moyennement qualifiés	Hautement qualifiés
Alimentation	27%	14%	4%
Habillement	6%	7%	2%
Logement	11%	14%	20%
Ameublement	12%	16%	18%
Soins de santé	9%	7%	4%
Transport	5%	5%	4%
Loisirs	24%	34%	46%
Culture et éducation	6%	3%	4%

Chaque catégorie de consommation listée dans le Tableau 7.17 a été associée à des produits et services disponibles sur EXIOBASE. La consommation finale des ménages françaises a été utilisée pour quantifier la consommation marginale de chaque groupe de ménage, respectant les distributions présentées dans le Tableau 7.17.

La nouvelle perturbation pour le second tour est donc la somme de la consommation induite des trois groupes de revenus, comme détaillé précédemment, avec des produits et services provenant du marché intérieur et également importés d'autres pays et régions. La liste d'activités incluses dans chaque catégorie est disponible dans le Chapitre 4.5 (p.130).

La matrice de flux de transactions (MFT) pour le deuxième tour de la première période est présentée pour le scenario Sc1.a pour illustrer le principe. Pourtant, tenant compte que le plus important est d'analyser les résultats à la fin de chaque période, la MFT comptabilisée à la fin de la première période est présentée pour le scenario Sc2.a dans cette section.

7.5.4.1 Scenario Sc1.a

Le Tableau 7.18 présente la TFM pour le deuxième cycle de la première période, c'est-à-dire la consommation induite, qui est surlignée en rouge. Une partie de l'argent va au ROW (€0,13 milliard) car les ménages importent des produits pour leur consommation finale. Par exemple, avec de l'argent supplémentaire, les ménages achètent des produits en cuir de l'Italie, de la nourriture et des véhicules en Allemagne, etc.

Tableau 7.18 | Matrice de flux de transactions, deuxième tour de la première période, Sc1.a (Source : Calculs de l'auteur à partir des équations développées dans la thèse)

(Milliard d'euros)	SNF		SF		AP-PR		AP-AS		MS						ROW		Σ
									FQ		MQ		HQ				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Dépenses de consommation finale		0.81							0.04		0.55		0.35			0.13	0
Formation brute de capital																	0
Exportations de biens et de services		0.00													0.00		0
Importations de biens et de services	0.08															0.08	0
Excédent d'exploitation	0.27	0.15		0.01				0.05		0.00		0.03		0.02	0.08	0.08	0
Salaires et rémunérations	0.30									0.02		0.14		0.14			0
Cotisations sociales de l'employeur	0.10							0.10									0
Impôts sur les produits	0.02							0.02							0.02	0.02	0
Autres impôts sur la production	0.04							0.04							0.00	0.00	0
Intérêts																	0
Impôts actuels sur le revenu, le patrimoine, etc.								0.08	0.00		0.04		0.04				0
Cotisations sociales								0.05	0.00		0.02		0.02				0
Prestations sociales																	0
Autres transactions																	0
Position nette non financière		0.15		0.01		0.00		0.34		-0.03		-0.44		-0.25		0.20	0
Dépôts	0.15		0.00	-0.01			0.34		-0.03		-0.44		-0.25		0.20		0
Dette																	0
Position nette non financière		-0.15		-0.01		0.00		-0.34		0.03		0.44		0.25		-0.20	0

Lors de ce second tour, les ménages consomment au total 0,95 milliard d'euros, 0,81 milliard en produits et services français et 0,13 milliard en biens et services importés. Dans l'économie française, cette consommation supplémentaire entraîne une augmentation de 0,004 milliard d'euros des exportations, 0,08 milliard d'euros des importations, 0,27 milliard d'euros de l'excédent d'exploitation, 0,30 des salaires et traitements, 0,10 des cotisations sociales patronales, 0,06 milliard d'euros de l'ensemble des impôts intérieurs. Ainsi, sur les 1,37 milliard d'euros qui ont été temporairement transférés sur les comptes financiers des ménages à la fin du premier tour, 0,82 milliard d'euros sont redistribués aux secteurs institutionnels français au second tour.

Les SNF et les SF sont en position créditrice nette puisqu'ils reçoivent une partie de l'excédent d'exploitation, ainsi que l'AP-AS qui, outre l'excédent d'exploitation, reçoit également les impôts. Les trois groupes de ménages sont en position d'emprunteur net, ce qui est attendu puisqu'ils ont besoin de l'argent du tour précédent pour financer leur consommation. Le solde global pour la première période, qui additionne le premier et le deuxième tour de distribution, est donc présenté dans le Tableau 7.19.

Tableau 7.19| Matrice de flux de transactions, fin de la première période, Sc1.a (Source : Calculs de l'auteur à partir des équations développées dans la thèse)

(Milliard d'euros)	SNF		SF		AP-PR		AP-AS		MS						ROW		Σ
									FQ		MQ		HQ				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Dépenses de consommation finale		0.81							0.04		0.55		0.35			0.13	0
Formation brute de capital		5.20			3.20				0.47		1.17		0.36				0
Exportations de biens et de services		0.03													0.03		0
Importations de biens et de services	1.18															1.18	0
Excédent d'exploitation	1.52	0.87		0.06				0.29		0.01		0.18		0.11	0.52	0.52	0
Salaires et rémunérations	2.19									0.10		1.23		0.85			0
Cotisations sociales de l'employeur	0.74							0.74									0
Impôts sur les produits	0.23							0.23							0.10	0.10	0
Autres impôts sur la production	0.19							0.19							0.03	0.03	0
Intérêts																	0
Impôts actuels sur le revenu, le patrimoine, etc.								0.54	0.02		0.31		0.21				0
Cotisations sociales								0.35	0.02		0.20		0.13				0
Prestations sociales					2.00					0.47		1.17		0.36			0
Autres transactions						2.08									2.08		0
Position nette non financière		0.87		0.06		-3.12		2.33		0.03		0.36		0.26		-0.79	0
Dépôts	0.59		0.00	0.27			1.33		0.03		0.36		0.26		-2.31		0
Dette	0.27		0.33			3.12	1.00								1.52		0
Position nette non financière		-0.87		-0.06		3.12		-2.33		-0.03		-0.36		-0.26		0.79	0

À la fin du premier tour, les SNF et les SF sont en position de prêt net résultant des deux tours de distribution, principalement en raison de l'excédent d'exploitation reçu à chaque tour. L'AP est en position d'emprunteur net en additionnant les deux fonctions. L'AP-PR est naturellement en position d'emprunteur net en raison de l'argent nécessaire pour investir dans le plan de relance, qui est partiellement récupéré par la (re)distribution monétaire (près de 75 % de l'argent emprunté est récupéré par l'AP-AS).

L'autre secteur institutionnel qui se trouve en position d'emprunteur net est le ROW, en raison de l'argent prêté pour financer le plan de relance. De même que le gouvernement, ils récupèrent une partie de l'argent prêté en raison de l'augmentation des importations des industries françaises et également des biens et services consommés par les ménages français.

Enfin, les trois catégories de revenus des ménages sont en position de prêt net, principalement parce que le gouvernement a financé toutes leurs dépenses initiales.

7.5.4.2 Scenario Sc2.a

La perturbation initiale pour la version détaillée est une augmentation de la formation brute de capital fixe de 5,80 milliards d'euros. À la fin du premier tour, cette perturbation a entraîné une augmentation de 0,10 milliard d'euros de la richesse nette temporaire des ménages faiblement qualifiés, provoquant une consommation induite de 0,07 milliard d'euros au second tour. Pour les ménages moyennement qualifiés, l'augmentation de la richesse au premier tour était de 1,20 milliard d'euros, induisant une consommation de 0,82 milliard d'euros. Le ménage hautement qualifié disposait de 1,31 milliard d'euros à la fin du premier tour, induisant une augmentation de la consommation de 0,91 milliard d'euros. Le Tableau 7.20 montre le solde final à la fin des premières périodes, en additionnant les transactions survenues au cours des premier et deuxième tours.

Tableau 7.20 | Matrice de flux de transactions, fin de la première période, Sc2.a (Source : Calculs de l'auteur à partir des équations développées dans la thèse)

(Milliard d'euros)	SNF		SF		AP-PR		AP-AS		MS						ROW		Σ
									FQ		MQ		HQ				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Dépenses de consommation finale		0,91							0,04		0,41		0,59			0,13	0
Formation brute de capital		5,80							0,71		3,40		1,68				0
Exportations de biens et de services		0,03													0,03		0
Importations de biens et de services	1,40															1,40	0
Excédent d'exploitation	1,57	0,89		0,07				0,30						0,31	0,61	0,61	0
Salaires et rémunérations	2,44									0,10		1,12		1,22			0
Cotisations sociales de l'employeur	0,82							0,82									0
Impôts sur les produits	0,27							0,27							0,12	0,12	0
Autres impôts sur la production	0,24							0,24							0,04	0,04	0
Intérêts																	0
Impôts actuels sur le revenu, le patrimoine, etc.								0,60	0,02		0,24		0,33				0
Cotisations sociales								0,39	0,02		0,18		0,19				0
Prestations sociales					2,00					0,47		1,17		0,36			0
Autres transactions						0,80									0,80		0
Position nette non financière		0,89		0,07		-1,20		2,61		-0,21		-1,95		-0,91		0,70	0
Dépôts	0,79		-0,01	3,87			2,23		0,03		0,29		0,41		0,12		0
Dette	0,10		3,93			1,20	0,38			0,24		2,24		1,33	0,58		0
Position nette non financière		-0,89		-0,05		1,20		-2,61		0,21		1,95		0,91		-0,70	0

Les SNF et les SF sont en position de prêt net, principalement en raison de l'excédent d'exploitation reçu. L'AP-PR et les trois groupes de ménages à revenus sont en position d'emprunteur net parce qu'ils contractent des prêts pour financer le plan de relance et les travaux de rénovation thermique, respectivement. Si l'on analyse l'ensemble, c'est-à-dire si l'on additionne la variation de richesse des deux fonctions, les administrations publiques présentent une augmentation significative de leur richesse nette. Le ROW bénéficie également de la perturbation dans cette première période.

1.1.1.1 *Scenario Sc3.a*

Les ménages reçoivent plus d'argent que dans la version détaillée en raison de la façon dont la valeur ajoutée est distribuée dans l'activité de travaux de construction. Par conséquent, dans cette version (c'est également le cas pour Sc3.b et Sc3.c), l'effet multiplicateur est de 1,4 % supérieur à celui observé dans la version détaillée, ce qui augmente le produit intérieur brut puisque la consommation induite est plus importante. Le Tableau 7.21 présente la MFT obtenue à la fin de la première période, pour le scénario Sc3.a.

Tableau 7.21 | Matrice de flux de transactions, fin de la première période, Sc3.a (Source : Calculs de l'auteur à partir des équations développées dans la thèse)

(Milliard d'euros)	SNF		SF		AP-PR		AP-AS		MS						ROW		Σ
									FQ		MQ		HQ				
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Dépenses de consommation finale		0,91							0,05		0,61		0,39			0,15	0
Formation brute de capital		5,80							1,38		3,39		1,04				0
Exportations de biens et de services		0,03													0,03		0
Importations de biens et de services	1,32															1,32	0
Excédent d'exploitation	1,70	0,97		0,07				0,33		0,01		0,20		0,12	0,58	0,58	0
Salaires et rémunérations	2,44									0,11		1,38		0,95			0
Cotisations sociales de l'employeur	0,82							0,82									0
Impôts sur les produits	0,25							0,25							0,12	0,12	0
Autres impôts sur la production	0,21							0,21							0,04	0,04	0
Intérêts																	0
Impôts actuels sur le revenu, le patrimoine, etc.								0,60	0,03		0,34		0,23				0
Cotisations sociales								0,39	0,02		0,22		0,15				0
Prestations sociales					2,00					0,47		1,17		0,36			0
Autres transactions						0,80									0,80		0
Position nette non financière		0,97		0,07		-1,20		2,60		-0,87		-1,82		-0,38		0,64	0
Dépôts	0,86		0,00	3,86			2,21		0,03		0,41		0,29		0,05		0
Dette	0,10		3,93			1,20	0,38			0,90		2,22		0,68	0,58		0
Position nette non financière		-0,97		-0,07		1,20		-2,60		0,87		1,82		0,38		0,64	0

7.6 Méthode appliquée à une étude de cas : transcription de la méthode

Résultats des impacts environnementaux et socio-économiques

L'impact environnemental évalué dans cette thèse est l'émission de gaz à effet de serre (GES), et les flux additionnels au sein de la technosphère sont les quantités de déchets générés

et la consommation d'énergie. La Figure 7.8 présente, pour rappel, les frontières du système des perturbations se produisant dans la première période (augmentation de la demande de travaux de rénovation thermique) et dans la deuxième période (économies d'énergie résultant de l'augmentation de l'efficacité énergétique).

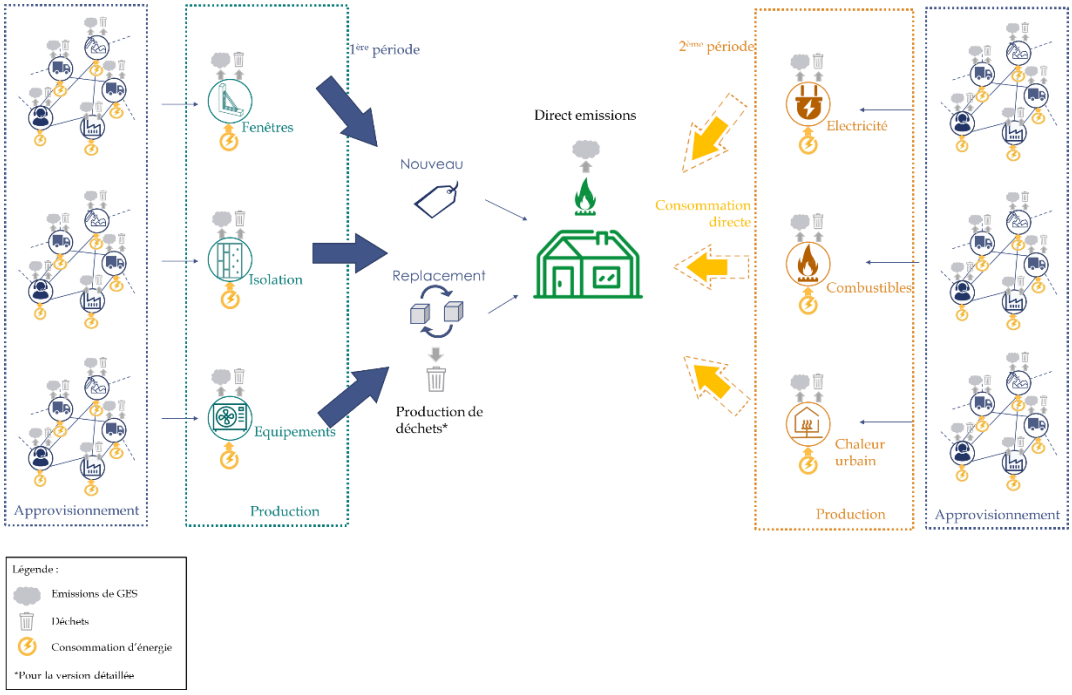


Figure 7.8 | Périmètre de l'étude du premier tour de la première période (côté gauche) et du premier tour de la deuxième période (côté droit)

Les résultats des trois versions présentent certaines similarités, comme on peut l'observer dans les graphiques de la Figure 7.9.

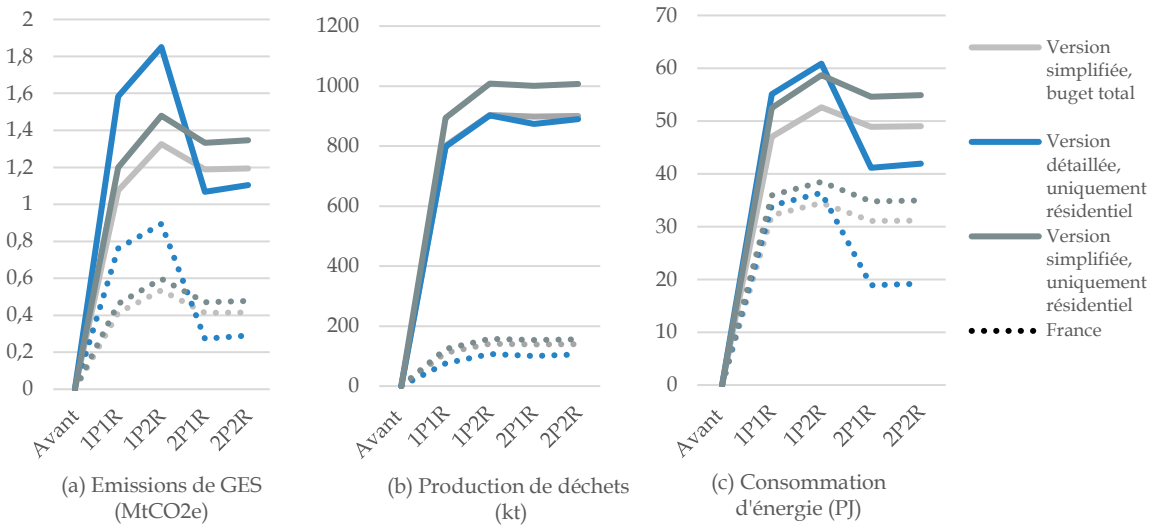


Figure 7.9 | Résultats des versions simplifiée et détaillée pour les émissions de GES, la consommation d'énergie et la production de déchets (Source : calculs effectués par l'auteur à partir des simulations réalisées dans la thèse)

Le premier point est que, pour les trois versions, les conséquences environnementales sont plus importantes au premier tour de la première période, mais que la consommation induite résultant de la redistribution des revenus est non négligeable pour les trois catégories d'impact évaluées. Le deuxième point commun est que les conséquences se produisant dans le reste du monde (ROW) suivent des modèles similaires pour les deux versions. Enfin, le troisième point concerne les résultats des scénarios proposés pour étudier la distribution de l'excédent d'exploitation aux ménages. Pour les trois versions, le scénario où l'excédent d'exploitation est versé à chaque groupe de revenus selon les proportions des salaires (scénarios 'a') présente l'impact environnemental le plus élevé pour les trois catégories. L'impact le plus faible est observé pour le scénario où l'excédent d'exploitation est épargné par les ménages car il n'induit pas de consommation.

La version étudiant le budget total du plan de relance (5,2 milliards d'euros dépensés par les ménages et le gouvernement pour améliorer l'efficacité énergétique des bâtiments publics et résidentiels) présente les plus faibles émissions de GES (1,075 $MtCO_2e$, dont 0,413 $MtCO_2e$ en France) et consommation d'énergie (47 PJ, dont 32 PJ en France), par rapport aux deux autres versions. La production de déchets dans cette version est de 802 kt au cours du premier tour de la première période, avec des tendances très similaires à celles de la version détaillée des bâtiments résidentiels ; cependant, cette dernière présente une réduction plus significative de la production de déchets au cours de la deuxième période en raison d'une baisse plus expressive de la consommation d'énergie.

Pour les versions étudiant la partie du budget consacrée aux bâtiments résidentiels (un total de 5,8 milliards d'euros de dépenses des ménages, 2,0 milliards d'euros provenant du plan de relance et 3,8 milliards d'euros provenant de leurs stocks), les émissions totales de GES étaient de 1,583 MtCO2e pour la version détaillée, dont 0,761 tCO_2e en France, et de 1,199 MtCO2e pour la version simplifiée, dont 0,461 $MtCO_2e$ en France. Ces chiffres représentent environ 1,01% pour la version détaillée et 0,61% pour la version simplifiée des émissions de GES du secteur français du bâtiment et de la construction en 2019 (75,1 $MtCO_2e$).

L'augmentation de la consommation d'énergie est de 55 PJ au premier tour de la première période de la version détaillée et de 52 PJ pour la version simplifiée. L'augmentation de la consommation d'énergie pour la production de produits et services français est de 34 PJ pour la version détaillée et de 36 PJ pour la version simplifiée. Ces chiffres représentent 1,25% de la consommation énergétique totale des bâtiments résidentiels et tertiaires en France (756 TWh), pour la version détaillée et 1,32% pour la version simplifiée.

Concernant les déchets, les flux supplémentaires produits par le plan de valorisation de l'efficacité thermique des bâtiments résidentiels sont de 798 kt pour la version détaillée et de 895 kt pour la version simplifiée. Les déchets produits en France sont de 76 kton dans la version détaillée et 124 kton dans la version simplifiée, représentant 0,18% (version détaillée) et 0,29% (version simplifiée) de la contribution annuelle totale du secteur en France (42 Mton).

La consommation induite de biens et services représente de 20% à 23% (versions simplifiées) et de 15% à 17% (version détaillée) des émissions de GES de premier ordre. Concernant la consommation d'énergie, la consommation induite représente de 10% à 12% (versions simplifiées) et de 9% à 10% (version détaillée) des effets de premier ordre. Enfin, concernant la production de déchets, les effets de second ordre représentent de 11% à 13% de la production de déchets de premier ordre pour les trois versions. Cela signifie que les effets de second ordre ne sont pas négligeables et doivent être pris en compte dans les nouvelles politiques.

L'importance relative de l'augmentation des émissions dans une première période suivie d'une réduction dans une seconde période a été analysée par rapport au budget carbone défini pour les bâtiments dans la Stratégie nationale bas carbone française. L'objectif fixé pour la période de 2019 à 2023 est une réduction de 422 $MtCO_2e$, dont 78 $MtCO_2e$ sont attribuées au secteur du bâtiment. La consommation induite de la première et de la deuxième période concerne l'ensemble de l'économie française, de sorte que la comparaison avec l'objectif d'un secteur en particulier est moins pertinente. Par conséquent, les résultats des émissions de GES du premier tour de la première période (1P1R) et du premier tour de la deuxième période (2P1R) présentés dans la Figure 7.9 ont été utilisés pour obtenir l'évolution des émissions de GES année par année, en considérant que le plan de relance a commencé à avoir un effet en 2021. En considérant que la réduction des émissions (2P1R) reste la même de 2022 à 2023, les résultats des trois versions de la perturbation pour la période de 2019 à 2023 sont présentés dans la Figure 7.10. Il convient de mentionner que les effets de premier ordre sont les mêmes pour les trois scénarios (a, b et c), ce qui justifie qu'une seule courbe soit présentée pour chaque version de la perturbation (1, 2 et 3).

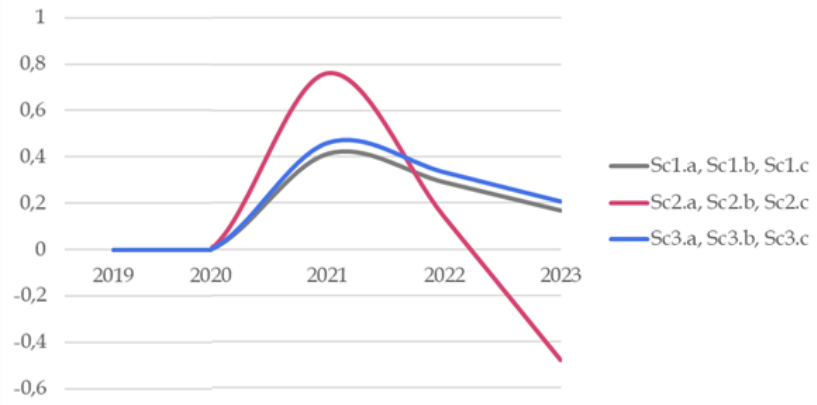


Figure 7.10 | Emissions de GES de 2019 à 2023 (MtCO2e) (Source : calculs de l'auteur à partir des simulations développées dans la thèse)

Les résultats présentés dans la Figure 7.10 montrent que les réductions de la consommation d'énergie ne compensent pas l'augmentation initiale pour les deux versions simplifiées. En revanche, pour la version détaillée, les émissions de GES économisées compensent l'augmentation initiale au cours du premier semestre 2022. Pour la version

détaillée, le plan de relance représente 1,4% du budget carbone total du secteur du bâtiment pour la période 2019-2023. Pour les deux autres versions, le plan de relance ne contribue pas à la réduction des émissions de GES pendant la période du budget carbone.

Les conséquences environnementales qui se produisent dans le reste du monde sont très importantes pour les trois enjeux environnementaux analysés ici, notamment pour la production de déchets. Pour cette dernière, 86% (versions simplifiées) à 90% (version détaillée) du total des déchets produits au cours du premier tour de la première période proviennent d'activités étrangères, principalement des minerais et concentrés de métaux précieux d'Asie, d'Amérique et d'Afrique dans les deux versions. Les déchets produits par la consommation induite sont également plus élevés dans le ROW qu'en France, cependant, ils tombent à environ 70% de la production totale de déchets pour les trois versions.

En conclusion, l'objectif principal de l'augmentation des travaux de rénovation thermique en France est de réduire la consommation d'énergie dans les années suivant l'application d'un travail de rénovation thermique donné. Les calculs présentés dans cette thèse ont montré que le temps nécessaire pour compenser les impacts environnementaux supplémentaires associés à l'augmentation des travaux de rénovation thermique varie significativement entre les trois indicateurs environnementaux évalués et entre les deux versions de la perturbation. Pour le budget total, en considérant uniquement les émissions françaises, le temps nécessaire est de 3,4 ans, alors que pour l'ensemble des émissions mondiales, il faudrait 7,8 ans pour compenser les émissions de premier ordre et 9,4 ans pour compenser les émissions de premier et second ordre.

Pour le budget consacré aux bâtiments résidentiels, la version détaillée, qui est plus précise en termes de technologies marginalement affectées, montre que 1,2 an est nécessaire pour compenser les émissions survenant en France. Si l'on considère la perspective globale, le temps nécessaire passe à 2,0 ans et à 2,4 ans en incluant les effets de second ordre. La version simplifiée des bâtiments résidentiels présente le temps le plus long nécessaire pour compenser l'augmentation des émissions. Les résultats montrent qu'il faut 3,6 ans pour compenser les émissions françaises, 8,2 ans si l'on considère la perspective mondiale et 9,9 ans si l'on inclut également les effets de second ordre.

En ce qui concerne la consommation d'énergie, le temps nécessaire est plus expressif. Si l'on considère la consommation d'énergie en France, la version du budget total montre que 9,5 ans sont nécessaires pour compenser l'augmentation de la consommation d'énergie en France, ce chiffre passant à 12,7 ans dans une perspective globale et à 14,2 ans si l'on tient également compte des effets de second ordre. Pour la version détaillée ne concernant que les bâtiments résidentiels, le temps nécessaire tombe à 1,9 an en France, à 2,8 ans d'un point de vue global et à 3,1 ans en tenant compte des effets de second ordre. Pour la version simplifiée, le temps nécessaire est de 9,8 ans en considérant la consommation d'énergie française, de 12,8 ans pour la consommation d'énergie mondiale et de 14,3 ans en incluant également les effets de second ordre.

Enfin, les résultats pour la production de déchets sont moins favorables puisque les réductions de déchets dues aux économies d'énergie sont moins importantes que celles observées pour les deux indicateurs précédents. La version budget total montre que 41,3 années sont nécessaires pour compenser l'augmentation de la production de déchets en France, 144 années d'un point de vue global et 162 années en considérant les effets de second ordre. Les réductions dans la version détaillée sont moins expressives pour les déchets, où 12 ans sont nécessaires en France, 28 ans dans le monde total et 31 ans en considérant les effets de second ordre. La version simplifiée présente des valeurs intermédiaires, car les économies réalisées sur la production de déchets sont plus élevées que pour le budget total et plus faibles que pour la version détaillée. Le temps nécessaire est de 33 ans pour compenser l'augmentation de la production de déchets en France, de 114 ans dans une perspective mondiale et de 128 ans en incluant également les effets de second ordre.

Impacts socio-économiques

Sur le plan socio-économique, dans la version simplifiée du budget total du plan de relance, nous nous sommes intéressés à comprendre comment l'argent supplémentaire provenant de l'Union européenne et des emprunts contractés par le gouvernement français pour financer le plan de relance français affecterait la richesse des secteurs institutionnels français. Nous avons donc considéré que l'argent injecté correspondait au budget total des bâtiments résidentiels publics et privés, soit 5,2 milliards d'euros. Cet argent supplémentaire ne paie qu'une partie des travaux de rénovation thermique; cependant, l'argent réel dépensé pour la rénovation n'a pas été pris en compte dans la version simplifiée car il n'était pas au centre de l'analyse. En revanche, dans la version détaillée, le champ de l'étude ne couvre que les bâtiments résidentiels, soit une augmentation de l'aide financière de 2 milliards d'euros, mais les informations sur les sommes effectivement dépensées pour les travaux de rénovation thermique ont été prises en compte. Par conséquent, la perturbation exogène pour la version détaillée était de 5,8 milliards d'euros, dont 2 milliards provenaient des aides financières et 3,8 milliards des stocks des ménages. Une troisième version de la perturbation a été construite pour comparer les approches adoptées dans les versions précédentes, où seuls les bâtiments résidentiels ont été étudiés en simplifiant les activités affectées au premier plan.

Les trois perturbations exogènes ne sont donc pas significativement différentes en termes d'ampleur, de sorte que la monnaie circulant dans l'économie est de 5,2 milliards d'euros pour la version simplifiée du budget total et de 5,8 milliards pour les deux versions étudiant uniquement les bâtiments résidentiels (simplifiée et détaillée). La principale différence entre les versions « budget total » et « uniquement résidentiel » réside dans le fait de savoir qui paie cet argent et d'où il provient, ce qui a donc un effet important sur les impacts socio-économiques. Les résultats présentés dans ce chapitre montrent que les ménages diminuent leur richesse nette depuis le début du plan de relance s'ils doivent financer une partie des travaux sur leurs propres stocks. En revanche, lorsque le gouvernement finance

l'ensemble des dépenses des ménages, ceux-ci augmentent leur richesse nette tour à tour, bénéficiant également des sommes dépensées pour la rénovation des bâtiments publics.

En général, les ménages moyennement qualifiés sont la catégorie de revenu la plus touchée. Dans la version simplifiée du budget total, l'augmentation de leur richesse nette est bien plus élevée que pour les deux autres groupes de revenus et, dans les deux versions « uniquement résidentielles », ils sont les plus endettés. Les ménages peu qualifiés sont le groupe de revenu le moins avantagé dans les trois versions. Toutefois, si l'on considère que le fait de recevoir (ou de souscrire) un euro supplémentaire a une utilité marginale plus élevée pour les ménages peu qualifiés que pour les autres groupes de revenus, lorsque l'on pondère les variations de la richesse nette par l'équité, les ménages peu qualifiés changent de position avec les ménages très qualifiés en ce qui concerne les gains de richesse. L'utilité totale pour le scénario où l'excédent d'exploitation est distribué à tous les ménages est plus élevée que pour le scénario où les ménages hautement qualifiés reçoivent la totalité de l'excédent d'exploitation. Il s'agit d'un compromis important en ce qui concerne les conséquences environnementales, dans lequel le scénario concentrant l'argent sur les ménages hautement qualifiés présente les plus faibles émissions de GES, consommation d'énergie et production de déchets.

En ce qui concerne les résultats comparant les équilibres financiers et les effets commerciaux, les deux versions de la perturbation présentent des résultats similaires en termes de ratios de monnaie prêtée par rapport à la balance commerciale. Le Luxembourg, le Japon et l'Irlande apparaissent avec les ratios les plus élevés, ce qui peut être considéré comme produisant des tensions potentielles car ils sont en quelque sorte impliqués dans le plan de relance en tant qu'agents de financement sans bénéficier des effets commerciaux.

7.7 Conclusions

Le secteur des bâtiments et de la construction fait partie des approches stratégiques visant à atteindre la neutralité carbone en 2050. Pour atteindre cet engagement ambitieux, les actions qui sont aujourd'hui appliquées dans une unité de produit de construction, d'équipement ou de bâtiment devront être appliquées dans des extensions plus importantes (décisions à grande échelle). Compte tenu de l'absence d'un cadre consensuel pour l'évaluation des conséquences environnementales des changements à grande échelle (majeurs) survenant dans le secteur de la construction, la principale motivation (et le premier objectif) de cette thèse était de répondre à la question de recherche présentée ci-dessous pour rappel.

« QR 1 - Comment évaluer les conséquences environnementales des changements majeurs dans le secteur de la construction afin d'aider à la prise de décision ? ».

Une revue de la littérature a été réalisée dans le but d'identifier ce qui a été fait dans d'autres secteurs en matière d'évaluation des conséquences environnementales des

changements à grande échelle, notamment les changements technologiques et les nouvelles politiques. Quarante articles utilisant l'ACV-C pour étudier des politiques ou des changements non marginaux ont été examinés. Les domaines qui apparaissent le plus fréquemment dans les résultats sont l'agriculture et les biocarburants, une raison possible de leur intérêt particulier pour l'approche conséquentielle étant de comprendre les effets indirects du changement d'affectation des terres. Globalement, les modèles économiques les plus fréquemment couplés à l'ACV sont les modèles d'équilibre (PE ou CGE), des modèles basés sur d'agents (ABM), l'analyse d'entrées-sorties (AES), pour étudier les effets sur les marchés, pour aller au-delà de la chaîne d'approvisionnement du produit et observer également les effets sur d'autres secteurs économiques. Cette partie de la recherche bibliographique était également axée sur la réponse à la deuxième et troisième question de recherche de cette thèse:

« QR2 - Quels sont les besoins méthodologiques pour l'application des approches d'ACV conséquentes au secteur de la construction ? ».

« QR3 - Comment modéliser la propagation des effets qui sont plus évidents pour les décisions à grande échelle ? ».

D'après les résultats de la revue bibliographique, les modèles économiques peuvent être très utiles pour aider à identifier les activités du système de produits qui devraient changer suite à un changement de la demande pour l'unité fonctionnelle étudiée. Alors que les modèles simples sont utiles pour identifier les principaux marchés affectés dans les limites normatives du système, des modèles économiques plus sophistiqués sont nécessaires pour inclure les effets indirects (effets de premier et de second ordre). Si les effets de premier ordre sont assez discutés dans la littérature ACV, très peu d'études analysent les effets de second ordre, tels que la redistribution des revenus, la croissance de la productivité et la relation entre ces deux.

Dans cette thèse, nous nous sommes limités aux effets de la redistribution des revenus, laissant la croissance de la productivité à des recherches futures. Considérant les limitations importantes des modèles d'équilibre computationnel lorsqu'il s'agit de la représentation du système financier, il est proposé d'utiliser de modèles Stock-Flux Cohérents (SFC) couplés au modèle d'entrées-sorties pour analyser les effets de second ordre d'un changement dans l'économie. Les modèles SFC prennent explicitement en compte la redistribution des revenus et peuvent fournir un cadre comptable cohérent pour décrire les effets d'un choc économique. En même temps, les modèles d'entrées-sorties sont appropriés pour analyser la relation entre l'économie et les sous-systèmes écologiques à travers les TES de l'extension environnementale et sont particulièrement compatibles avec l'ACV.

7.7.1 Contributions scientifiques

Les principales contributions de cette thèse ont été, premièrement, de **proposer un cadre non ambigu pour évaluer les effets de premier et de second ordre (effets de distribution des revenus)** et, deuxièmement, de **le tester dans le cas d'une nouvelle politique concernant le secteur de la construction**.

Comme évoqué précédemment, les modèles SFC prennent explicitement en compte la redistribution des revenus et fournissent un cadre comptable cohérent pour décrire les effets d'une perturbation économique. Le cadre SFC garantit que les soldes monétaires sont effectivement cohérents car chaque flux monétaire est enregistré comme un revenu pour quelqu'un et un résultat pour quelqu'un d'autre. De plus, le cadre SFC permet de relier les cycles de distribution de manière cohérente, les changements dans les stocks étant comptabilisés comme le résultat des changements dans les flux (reliant les aspects financiers et non financiers de l'économie).

Puisque la modélisation conséquentielle concerne la façon dont les processus sont liés, les tableaux d'entrées-sorties multirégionaux étendus à l'environnement peuvent être considérés comme parfaitement compatibles avec l'ACV conséquentielle, surtout s'ils sont construits sur la base de la construction technologique des produits de base ou de la construction technologique des sous-produits. Dans la méthode proposée dans cette thèse, EXIOBASE a été sélectionné car il est disponible publiquement et bien documenté, couvrant un grand nombre de pays et de régions, ainsi qu'un grand nombre d'émissions de substances et de catégories de consommation de ressources.

EXIOBASE fournit un grand nombre de flux, mais aucune information sur les stocks, pour cette raison, **l'une des contributions de cette thèse a été de construire une « base de données de stocks »** cohérente avec la modélisation proposée pour obtenir la redistribution monétaire.

Même en considérant que le jeu de données sélectionné pour obtenir les résultats présentés ici n'était pas idéalement construit selon les caractéristiques souhaitées pour la modélisation (qui sont discutées dans le chapitre 1), le choix d'utiliser les tableaux d'entrées-sorties monétaires est justifié par le fait qu'ils sont les plus récents disponibles et aussi parce que, avec les tableaux d'entrées-sorties monétaires, les effets du commerce peuvent être comparés avec les changements de stocks obtenus avec la base de données de stocks. Idéalement, la version hybride devrait être convertie en version monétaire, en multipliant chaque production intermédiaire par son prix de base, afin qu'une version monétaire équivalente soit utilisée dans la méthodologie développée dans cette thèse.

A ce sujet, une analyse de sensibilité a été menée pour étudier comment les résultats varient en utilisant une version hybride des tableaux d'entrées-sorties. Des différences importantes ont été observées sur les principaux contributeurs aux impacts

environnementaux. Le tableau hybride des entrées-sorties présente les sous-produits comme des entrées négatives, ce qui entraîne des émissions de GES différentes lorsque la coproduction est importante (par exemple, les cendres volantes dans la fabrication de ciment).

Par conséquent, le principal résultat de cette thèse est la définition d'un cadre permettant d'évaluer les effets de premier et de second ordre (effets de la distribution des revenus). Le cadre général est illustré dans

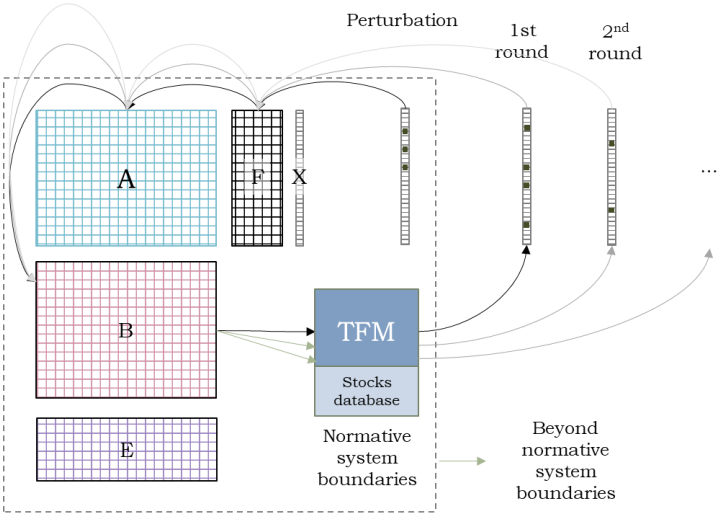


Figure 7.11 | Structure de la distribution monétaire (Source : illustration développée par l'auteur)

La matrice A représente la matrice des coefficients technologiques, avec les intrants requis par unité de production de chaque activité. Les matrices B et E sont les extensions du tableau IO, où B présente les coefficients des éléments de valeur ajoutée et E les coefficients des émissions de substances par unité de production. F représente les éléments de la demande finale, et X les sorties totales, qui sont égales aux entrées totales pour la version monétaire. Toutes ces matrices sont obtenues à partir d'EXIOBASE.

Ce cadre est formalisé dans une méthode en 5 étapes, décrite ci-dessous :

- Étape 1 : Définition de la perturbation exogène
- Étape 2 : Détermination des transactions qui sont incluses dans le modèle
- Étape 3 : Calcul de la distribution monétaire à partir de modèles IO
- Étape 4 : Comptabilisation des changements de flux dans une matrice des flux de transactions
- Étape 5 : Calcul de la redistribution des revenus

La première étape consiste à définir la perturbation exogène, qui doit représenter l'unité fonctionnelle en fonction des objectifs et de la portée de l'étude. La deuxième étape consiste à déterminer les transactions qui feront partie de l'étude et à sélectionner les secteurs institutionnels pertinents pour l'étude. La troisième étape consiste à intégrer un modèle de distribution monétaire, qui est codé en Python. La quatrième étape consiste à comptabiliser les changements dans les flux dans une matrice des flux de transactions (MFT) et à analyser les

changements dans les stocks qui affecteront un autre cycle de distribution, appelé redistribution (étape 5).

7.7.2 Contributions techniques

Le second objectif de la thèse était d'appliquer la méthode à une étude de cas dans le secteur de la construction. Considérant l'effet substantiel de la pandémie de Covid 19 sur l'économie mondiale, la méthodologie a été appliquée au plan de relance français, en particulier le budget dédié à la promotion et à l'accélération de la rénovation thermique sur le territoire national. Le plus grand défi était d'identifier comment le plan de relance affecte directement les activités économiques françaises, en particulier pour quantifier l'argent que les ménages dépensent en produits de rénovation thermique. Pour cela, deux hypothèses principales ont été faites, représentées par les trois versions de la perturbation exogène.

Dans la première, appelée « version simplifiée, budget total », la totalité du budget du plan de relance a été considérée comme la perturbation exogène (5,2 milliards d'euros), en considérant à la fois les bâtiments résidentiels et publics. Dans cette version, l'hypothèse était que l'argent du plan de relance reçu par les ménages et les acteurs gouvernementaux est égal à la valeur dépensée par eux dans les travaux de rénovation thermique. Une deuxième hypothèse importante était que l'activité appelée « travaux de construction » était la seule affectée par la perturbation exogène, sans aller plus loin dans l'analyse des types de travaux favorisés par le plan de relance.

Dans la deuxième version, appelée « version détaillée, uniquement résidentiel », le montant de chaque produit et équipement de rénovation thermique a été obtenu à partir d'un modèle économétrique développé pour quantifier les travaux de rénovation thermique induits par les aides financières, à savoir MENFIS (décrit au chapitre 4) ; cependant, seul le budget dédié aux bâtiments résidentiels (2,0 milliards d'euros) est considéré dans cette version. Selon les simulations du MENFIS, une augmentation des aides financières de 2,0 milliards d'euros augmente les dépenses des ménages en travaux de rénovation thermique de 5,8 milliards d'euros, ce qui était la valeur de la perturbation exogène pour cette deuxième version. Cette version permet d'identifier les activités marginalement affectées par la politique publique, en montrant un écart essentiel entre les aides financières et les sommes effectivement dépensées par les ménages.

La troisième version, appelée « version simplifiée, uniquement résidentielle », combine des éléments des deux versions précédentes. Comme l'indique explicitement le nom de la version, le champ d'application du plan de relance est le budget consacré aux bâtiments résidentiels. A titre de comparaison, la valeur prise en compte dans cette version est la même que dans la deuxième version, soit 5,80 milliards d'euros. La différence avec la version précédente est que la seule activité affectée dans la perturbation exogène est celle des « travaux de construction ». Cette version est utile dans le cas où une estimation simplifiée des

conséquences environnementales d'une augmentation de la demande pour une activité de construction quelconque, comme les travaux de rénovation thermique.

Les résultats des trois versions présentent quelques similitudes. Le premier point est que, dans les deux versions, les conséquences environnementales étaient plus significatives dans le premier tour de la première période, c'est-à-dire des effets de premier ordre, cependant, la consommation induite résultant de la redistribution des revenus est non négligeable pour les trois questions environnementales évaluées ici. Le deuxième point commun est que les conséquences se produisant dans le reste du monde suivent des schémas similaires pour les trois versions avec de légères différences.

L'augmentation des émissions de GES obtenue par la méthode présentée dans cette thèse est de 1,075 MtCO2e pour la version simplifiée du budget total, de 1,583 MtCO2e pour la version détaillée uniquement résidentiel et 1,199 MtCO2e pour la version simplifiée uniquement résidentiel. La part des émissions survenant en France était de 0,413 MtCO2e, 0,761 MtCO2e et 0,461 MtCO2e, pour les trois versions, respectivement. Ces chiffres représentent environ 0,55%, pour la version simplifiée du budget total, et 1,01%, pour la version détaillée et 0,61%, pour la version simplifiée uniquement résidentiel, des émissions de GES du secteur français du bâtiment et de la construction en 2019 (75,1 MtCO2e).

L'augmentation de la consommation d'énergie est de 47 PJ comme effets de premier ordre dans la version simplifiée du budget total, de 55 PJ dans la version détaillée et 53 PJ dans la version simplifiée du budget relatif aux bâtiments résidentiels. L'augmentation de la consommation d'énergie pour la production de produits et services français est de 32,2 PJ pour la version simplifiée du budget total, de 34,0 PJ pour la version détaillée et 36,0 PJ pour la version simplifiée uniquement résidentiel. Ces chiffres représentent 1,18% de la consommation énergétique totale des bâtiments résidentiels et tertiaires en France (756 TWh), pour la version simplifiée du budget total, 1,25% pour la version détaillée et 1,32% pour la version simplifiée uniquement résidentiel.

En ce qui concerne les déchets, les flux supplémentaires de déchets produits sont de 802 kt pour la version simplifiée du budget total, de 798 kt pour la version détaillée et 895 kt pour la version simplifiée du budget dédié aux bâtiments résidentiels. Les déchets produits en France sont de 111 kt dans la version simplifiée, de 76 kt dans la version détaillée et 124 kton dans la version simplifiée uniquement résidentiel, soit 0,26% (version simplifiée, budget total), 0,18% (version détaillée, uniquement résidentiel) et 0,29% (version simplifiée, uniquement résidentiel) de la contribution annuelle totale du secteur en France (42 Mt).

La consommation induite de biens et services représente de 20% à 23% (versions simplifiées) et de 15% à 17% (version détaillée) des émissions de GES de premier ordre. Concernant la consommation d'énergie, la consommation induite représente de 10% à 12% (version simplifiée) et de 9% à 10% (version détaillée) des effets de premier ordre. Enfin, concernant la production de déchets, les effets de second ordre représentent de 11% à 13% de

la production de déchets de premier ordre, pour les deux versions. Cela signifie que les effets de second ordre ne sont pas négligeables et doivent être pris en compte dans les nouvelles politiques.

7.7.3 Discussions et Limitations

Les résultats présentés dans cette thèse ont quelques limitations qui sont détaillées ici. La première concerne la base de données sélectionnée et utilisée pour effectuer les calculs. Le tableau des entrées-sorties monétaires de la version pymrio est construit en utilisant l'hypothèse de technologie industrielle, qui suppose qu'une industrie fabrique ses produits en utilisant la même technologie et divise les sorties en fonction de leur valeur économique, similaire à l'allocation économique en ACV. Par conséquent, elle viole l'une des caractéristiques souhaitées de la base de données conséquentielle, qui consiste à favoriser la substitution au lieu de toute allocation de partitionnement.

La deuxième limite consiste en un manque de validation des résultats présentés dans cette thèse. Considérant que le plan de relance français se concentre sur la création d'emplois et la croissance économique, le modèle présenté ici permet d'identifier les boucles de rétroaction potentielles qui augmentent le pouvoir d'achat des ménages, cependant, comme le plan couvre d'autres activités économiques et que nous nous sommes concentrés uniquement sur la partie de la rénovation thermique, il est difficile de valider les résultats de ce qui a été observé dans la réalité.

Idéalement, lors de la réalisation d'une ACV basée sur la modélisation des entrées-sorties, il est recommandé d'endogénéiser les produits impactés. Cela n'a pas été fait dans cette thèse parce que la modélisation a été réalisée en utilisant les tables d'entrées-sorties d'Exiobase et qu'une importante collecte de données a été nécessaire pour modéliser tous les produits et équipements qui sont affectés par l'augmentation des travaux de rénovation thermique.

De plus, un niveau élevé d'incertitude est souvent cité comme une limitation majeure de l'ACV conséquentielle. Aucune analyse d'incertitude n'a été réalisée dans cette thèse malgré la grande importance du sujet. Ceci est souligné comme une limite de la thèse car elle a été laissée hors du champ de l'étude, et une place pour un travail ultérieur.

7.7.4 Perspectives

Cette thèse démontre qu'il est possible d'évaluer les effets de second ordre dans un cadre transparent et sans ambiguïté. Cependant, elle ouvre la voie à de nouvelles recherches sur les plans scientifique et technique. Les recommandations de recherche identifiées sont détaillées ci-après.

7.7.4.1 Perspectives et opportunités scientifiques

Le premier point identifié concerne la désagrégation des agents inclus dans l'économie étudiée. Il existe quelques modèles SFC basés sur les agents disponibles publiquement qui pourraient être couplés avec la méthodologie développée ici afin de fournir une meilleure simulation du comportement des agents.

Un ensemble de données sur l'empreinte sociale compatible avec les activités d'EXIOBASE est disponible publiquement depuis février 2022, ce qui permet de réaliser une empreinte sociale complète. Cela a été laissé en dehors du cadre de cette thèse, cependant il serait important de comparer les effets distributifs purs tels qu'évalués dans cette thèse avec l'empreinte sociale complète décrite dans Weidema (2018). Pour cela, les calculs devraient être effectués avec la version hybride (ou son équivalent monétaire) basée sur les mêmes produits que la base de données de l'empreinte sociale (Weidema, 2022).

En outre, les liens entre les empreintes sociales et environnementales et les Objectifs de développement durable (ODD) basés sur les activités d'EXIOBASE sont également accessibles au public depuis février 2022 (Weidema, 2022). Ces liens ont également été laissés en dehors du champ de la présente recherche, cependant, compte tenu de l'importance d'avoir une meilleure compréhension de la contribution des politiques aux ODD, l'une des recommandations est d'intégrer ces liens dans la méthodologie développée ici.

Les effets de second ordre évalués dans la méthodologie proposée ont laissé le problème de la croissance de la productivité à des recherches futures plus approfondies. L'argent supplémentaire dans les stocks des secteurs institutionnels peut être investi dans la production, contribuant ainsi à la croissance de la productivité. Le principal problème identifié ici est l'absence d'une fonction d'investissement consensuelle reliant la variation des stocks à la productivité. Il s'agit d'une opportunité pour des recherches futures car les décisions sur la façon dont l'argent est investi peuvent présenter différentes conséquences environnementales et sociales.

7.7.4.2 Perspectives et opportunités techniques

Dans l'étape d'analyse du cycle de vie, la contribution du plan de relance aux émissions de GES a été comparée aux objectifs de la stratégie nationale pour un faible niveau de carbone. Cette comparaison n'a pas été facile à faire car le secteur de la construction touche différents secteurs concernés par les objectifs. Il est donc recommandé de mettre en place un système commun de comptabilisation des émissions de gaz à effet de serre afin d'identifier comment une politique donnée contribuera effectivement à la réduction globale des émissions, de la consommation d'énergie et de la production de déchets.

L'une des limites identifiées de cette thèse est que nous avons simplifié la perturbation exogène en affectant les produits déjà endogénisés. Cela a été fait en raison du manque de données pour endogénéiser les produits de construction dans le tableau des entrées-sorties. Par conséquent, une recommandation de la recherche actuelle est de recueillir des données

pour fournir des informations plus précises sur la valeur ajoutée d'un produit de construction donné et aussi des éléments de la demande finale (par exemple, la formation brute de capital fixe, et les demandes spécifiques pour chaque produit de construction divisé par groupe de revenu).

Enfin, cette thèse s'est concentrée sur trois indicateurs environnementaux, tandis que d'autres questions environnementales significatives pour le secteur de la construction, qui pourraient également être couvertes par la méthode, ont été laissées pour des travaux ultérieurs. C'est le cas, par exemple, du changement d'affectation des sols, dont la méthodologie bien établie est couverte par EXIOBASE (Schmidt and De Rosa, 2018) et qui pourrait être très utile dans les études d'artificialisation des sols et les évaluations de la biodiversité.

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Appendix 1 – List of Publications

I- Peer-reviewed journals

Almeida, Denise T.L., Bo P. Weidema, and Antoine Godin. 2022. "Beyond Normative System Boundaries in Life Cycle Assessment: The Environmental Effect of Income Redistribution." Cleaner Environmental Systems 4 (November 2021): 100072. https://doi.org/10.1016/j.cesys.2022.100072.

Almeida, D. T. L., Charbuillet, C., Marotte, C., Lebert, A., & Perry, N. Consequential Life Cycle Assessment applied to the construction sector: a literature review (to be sumitted)

Almeida, D. T. L., Weidema, B.P., Godin A., Pellan, M., Charbuillet, C., Marotte, C., & Perry, N. Assessing environmental consequences of ecological transition policies: the role of stocks (to be submitted)

II- Conference papers

ADEME, 2020. Survey on the Evolution of Wood Fuel Prices in 2019-2020.

Albers, A., Collet, P., Lorne, D., Benoist, A., Hélias, A., 2019. Coupling partial-equilibrium and dynamic biogenic carbon models to assess future transport scenarios in France. Appl. Energy 239, 316–330. https://doi.org/10.1016/j.apenergy.2019.01.186

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III- Communication

Oral presentation | The 10th international conference on life cycle management (LCM 2021). Section: Construction and Renovation of Buildings. Stuttgart, Germany/ web-conference (due to Covid pandemics). September 2021.

Oral presentation | The 27th CIRP Life Cycle Engineering Conference (LCE 2020). LCA section of May 15th 2020. Grenoble, France/web-conference (due to Covid pandemics). May 2020.

Poster | The 9th international conference on life cycle management (LCM 2021). Section: T2-9 Sustainability in the Construction Sector. Poznan, Poland. September 2019.

Appendix 2 – EXIOBASE 3 activities

Paddy rice	Coking Coal	Sand and clay	Secondary paper for treatment. Re-processing of secondary paper into new pulp	Bitumen	Cement. lime and plaster
Wheat	Other Bituminous Coal	Chemical and fertilizer minerals. salt and other mining and quarrying products n.e.c.	Paper and paper products	Paraffin Waxes	Ash for treatment. Re-processing of ash into clinker
Cereal grains n.e.c.	Sub-Bituminous Coal	Products of meat cattle	Printed matter and recorded media (22)	Petroleum Coke	Other non-metallic mineral products
Vegetables. fruit. nuts	Patent Fuel	Products of meat pigs	Coke Oven Coke	Non-specified Petroleum Products	Basic iron and steel and of ferro-alloys and first products thereof
Oil seeds	Lignite/Brown Coal	Products of meat poultry	Gas Coke	Nuclear fuel	Secondary steel for treatment. Re-processing of secondary steel into new steel
Sugar cane. sugar beet	BKB/Peat Briquettes	Meat products n.e.c.	Coal Tar	Plastics. basic	Precious metals
Plant-based fibers	Peat	products of Vegetable oils and fats	Motor Gasoline	Secondary plastic for treatment. Re-processing of secondary plastic into new plastic	Secondary preciuos metals for treatment. Re-processing of secondary preciuos metals into new preciuos metals
Crops n.e.c.	Crude petroleum and services related to crude oil extraction. excluding surveying	Dairy products	Aviation Gasoline	N-fertiliser	Aluminium and aluminium products
Cattle	Natural gas and services related to natural gas extraction. excluding surveying	Processed rice	Gasoline Type Jet Fuel	P- and other fertiliser	Secondary aluminium for treatment. Re-processing of secondary aluminium into new aluminium
Pigs	Natural Gas Liquids	Sugar	Kerosene Type Jet Fuel	Chemicals n.e.c.	Lead. zinc and tin and products thereof
Poultry	Other Hydrocarbons	Food products n.e.c.	Kerosene	Charcoal	Secondary lead for treatment. Re-processing of secondary lead into new lead
Meat animals n.e.c.	Uranium and thorium ores (12)	Beverages	Gas/Diesel Oil	Additives/Blending Components	Copper products
Animal products n.e.c.	Iron ores	Fish products	Heavy Fuel Oil	Biogasoline	Secondary copper for treatment. Re-processing of secondary copper into new copper

Raw milk	Copper ores and concentrates	Tobacco products (16)	Refinery Gas	Biodiesels	Other non-ferrous metal products
Wool. silk-worm cocoons	Nickel ores and concentrates	Textiles (17)	Liquefied Petroleum Gases (LPG)	Other Liquid Biofuels	Secondary other non-ferrous metals for treatment. Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
Manure (conventional treatment)	Aluminium ores and concentrates	Wearing apparel; furs (18)	Refinery Feedstocks	Rubber and plastic products (25)	Foundry work services
Manure (biogas treatment)	Precious metal ores and concentrates	Leather and leather products (19)	Ethane	Glass and glass products	Fabricated metal products. except machinery and equipment (28)
Products of forestry. logging and related services (02)	Lead. zinc and tin ores and concentrates	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	Naphtha	Secondary glass for treatment. Re-processing of secondary glass into new glass	Machinery and equipment n.e.c. (29)
Fish and other fishing products; services incidental of fishing (05)	Other non-ferrous metal ores and concentrates	Wood material for treatment. Re-processing of secondary wood material into new wood material	White Spirit & SBP	Ceramic goods	Office machinery and computers (30)
Anthracite	Stone	Pulp	Lubricants	Bricks. tiles and construction products. in baked clay	Electrical machinery and apparatus n.e.c. (31)

Appendix 3 – Transactions-flow matrix of France, 2020

Transactions-flow matrix of France, 2020, in MEUR

	Non Financial Corporations		Financial Corporations		Government		Households		Non profit institutions		Rest of World		Total
	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	Use	Res	
Output	0	2739202	0	241749	0	516732	0	449459	0	54334	0	0	4001476
Intermediate consumption	1570911	0	156221	0	123024	0	80322	0	16726	0	0	0	-1947204
Final consumption expenditure	0	1801000	0	0	577296	0	1175006	0	48698	0	0	0	0
Gross capital formation	302307	548357	22640	0	88084	0	130363	0	4963	0	0	0	0
Exports of goods and services	0	641891	0	0	0	0	0	0	0	0	641891	0	0
Imports of goods and services	688412	0	0	0	0	0	0	0	0	0	0	688412	0
Value-added, gross	885981			85528		393708		369137		37608	0	0	0
Wages and salaries	595257	0	40061	0	204868	0	30295	909201	23891	0	16402	1573	0
Employers' social contributions	168846	0	14572	0	99182	0	9688	305682	8001	0	5440	47	0
Taxes on products	274057	0	0	0	0	271992	0	0	0	0	0	2065	0
Other taxes on production	72950	0	12516	0	11554	117925	22642	0	1251	0	0	2988	0
Subsidies on products	0	25468	0	0	24236	0	0	0	0	0	1232	0	0
Other subsidies on production	0	40130	0	122	54145	2924	0	17677	0	287	6995	0	0
Interest	56521	47055	90965	125744	29624	1919	12421	12197	98	632	52291	54373	0
Distributed income of corporations	161737	127928	22514	35878	0	5501	0	32752	0	NA	49893	32085	0
Reinvested earnings on direct foreign investment	3060	-1516	-220	1282	0	-520	NA	NA	NA	NA	-754	2840	0
Property income attributed to insurance policy holders	NA	1109	56292	14953	NA	1186	NA	39761	NA	84	3392	2591	0
Rents	4414		NA	NA	182	3206	1516	2906	NA	NA	0	0	0
Current taxes on income, wealth, etc.	43446	0	17846	0	65	304391	240092	0	NA	0	2942	NA	0
Social contributions	0	13128	0	36140	0	392813	449314	9	0	NA	241	7465	0
Social benefits other than social transfers in kind	13037	0	36140	0	519635	0	9	569356	457	0	7474	7396	0
Other current transfers	42935	22409	102251	101331	92043	17908	71873	73829	1418	50201	18193	63035	0
Adjustment for the change in pension entitlements	NA	0	NA	0	NA	0	NA	NA	NA	0	NA	NA	0
Capital transfers	3189	29197	49	2310	24418	5773	16897	5975	NA	2197	1958	1059	0
Acquisitions less disposals of non-financial non-produced assets	NA	0	15	0	2624	0	-2639	0	NA	0	NA	0	0
Net lending (+) /net borrowing (-)		-19993		-12353		-209230		181005		2232		58339	0

Monetary gold and special drawing rights (SDRs)	NA	NA	74	NA	NA	NA	NA	NA	NA	NA	NA	74	0
Currency and deposits	187108	NA	151925	529821	76278	118	155020	NA	9994	NA	115537	165922	-1
Debt securities	-3718	78968	351523	50818	-1843	292174	-626	NA	494	NA	169700	93569	-1
Loans	16593	148872	193705	47395	4071	2697	403	70605	NA	1542	50697	-5642	0
Equity and investment fund shares	110686	84134	61532	62902	1016	NA	26098	NA	-129	NA	28347	80514	0
Insurance, pensions and standardised guarantees	6955	NA	237	22544	406	237	12842	NA	2	NA	2338	NA	1
Financial derivatives and employee stock options	NA	NA	137501	161589	777	524	NA	NA	NA	NA	160812	136977	0
Other accounts receivable / payable	-8479	12512	3796	40206	22821	10936	66884	19646	2	NA	-8802	-7078	0
Discrepancy with the financial net lending/net borrowing (B9F-B9)	0	0	0	0	0	0	0	0	0	0	0	0	0
Net financial transactions	0	-15342	0	-14981	0	-203160	0	170368	0	8821	0	54294	0

Appendix 4 - Phi matrix

	NFC	FC	GG	HH	NPISH
Paddy rice	1,00	0	0	0	0,00
Wheat	1,00	0	0	0	0,00
Cereal grains n.e.c.	1,00	0	0	0	0,00
Vegetables, fruit, nuts	1,00	0	0	0	0,00
Oil seeds	1,00	0	0	0	0,00
Sugar cane, sugar beet	1,00	0	0	0	0,00
Plant-based fibers	1,00	0	0	0	0,00
Crops n.e.c.	1,00	0	0	0	0,00
Cattle	1,00	0	0	0	0,00
Pigs	1,00	0	0	0	0,00
Poultry	1,00	0	0	0	0,00
Meat animals n.e.c.	1,00	0	0	0	0,00
Animal products n.e.c.	1,00	0	0	0	0,00
Raw milk	1,00	0	0	0	0,00
Wool, silk-worm cocoons	1,00	0	0	0	0,00
Manure (conventional treatment)	1	0	0	0	0
Manure (biogas treatment)	1	0	0	0	0
Products of forestry, logging and related services (02)	1	0	0	0	0
Fish and other fishing products; services incidental of fishing (05)	1	0	0	0	0
Anthracite	1	0	0	0	0
Coking Coal	1	0	0	0	0
Other Bituminous Coal	1	0	0	0	0
Sub-Bituminous Coal	1	0	0	0	0
Patent Fuel	1	0	0	0	0
Lignite/Brown Coal	1	0	0	0	0
BKB/Peat Briquettes	1	0	0	0	0
Peat	1	0	0	0	0
Crude petroleum and services related to crude oil extraction, excluding surveying	1	0	0	0	0
Natural gas and services related to natural gas extraction, excluding surveying	1	0	0	0	0
Natural Gas Liquids	1	0	0	0	0
Other Hydrocarbons	1	0	0	0	0
Uranium and thorium ores (12)	1	0	0	0	0
Iron ores	1	0	0	0	0
Copper ores and concentrates	1	0	0	0	0
Nickel ores and concentrates	1	0	0	0	0
Aluminium ores and concentrates	1	0	0	0	0
Precious metal ores and concentrates	1	0	0	0	0
Lead, zinc and tin ores and concentrates	1	0	0	0	0
Other non-ferrous metal ores and concentrates	1	0	0	0	0
Stone	1	0	0	0	0
Sand and clay	1	0	0	0	0
Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	1	0	0	0	0
Products of meat cattle	1	0	0	0	0
Products of meat pigs	1	0	0	0	0
Products of meat poultry	1	0	0	0	0
Meat products n.e.c.	1	0	0	0	0
products of Vegetable oils and fats	1	0	0	0	0
Dairy products	1	0	0	0	0
Processed rice	1	0	0	0	0
Sugar	1	0	0	0	0
Food products n.e.c.	1	0	0	0	0
Beverages	1	0	0	0	0
Fish products	1	0	0	0	0
Tobacco products (16)	1	0	0	0	0
Textiles (17)	1	0	0	0	0
Wearing apparel; furs (18)	1	0	0	0	0
Leather and leather products (19)	1	0	0	0	0
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	1	0	0	0	0
Wood material for treatment, Re-processing of secondary wood material into new wood material	1	0	0	0	0
Pulp	1	0	0	0	0
Secondary paper for treatment, Re-processing of secondary paper into new pulp	1	0	0	0	0
Paper and paper products	1	0	0	0	0
Printed matter and recorded media (22)	1	0	0	0	0
Coke Oven Coke	1	0	0	0	0
Gas Coke	1	0	0	0	0

Coal Tar	1	0	0	0	0
Motor Gasoline	1	0	0	0	0
Aviation Gasoline	1	0	0	0	0
Gasoline Type Jet Fuel	1	0	0	0	0
Kerosene Type Jet Fuel	1	0	0	0	0
Kerosene	1	0	0	0	0
Gas/Diesel Oil	1	0	0	0	0
Heavy Fuel Oil	1	0	0	0	0
Refinery Gas	1	0	0	0	0
Liquefied Petroleum Gases (LPG)	1	0	0	0	0
Refinery Feedstocks	1	0	0	0	0
Ethane	1	0	0	0	0
Naphtha	1	0	0	0	0
White Spirit & SBP	1	0	0	0	0
Lubricants	1	0	0	0	0
Bitumen	1	0	0	0	0
Paraffin Waxes	1	0	0	0	0
Petroleum Coke	1	0	0	0	0
Non-specified Petroleum Products	1	0	0	0	0
Nuclear fuel	1	0	0	0	0
Plastics, basic	1	0	0	0	0
Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	1	0	0	0	0
N-fertiliser	1	0	0	0	0
P- and other fertiliser	1	0	0	0	0
Chemicals n.e.c.	1	0	0	0	0
Charcoal	1	0	0	0	0
Additives/Blending Components	1	0	0	0	0
Biogasoline	1	0	0	0	0
Biodiesels	1	0	0	0	0
Other Liquid Biofuels	1	0	0	0	0
Rubber and plastic products (25)	1	0	0	0	0
Glass and glass products	1	0	0	0	0
Secondary glass for treatment, Re-processing of secondary glass into new glass	1	0	0	0	0
Ceramic goods	1	0	0	0	0
Bricks, tiles and construction products, in baked clay	1	0	0	0	0
Cement, lime and plaster	1	0	0	0	0
Ash for treatment, Re-processing of ash into clinker	1	0	0	0	0
Other non-metallic mineral products	1	0	0	0	0
Basic iron and steel and of ferro-alloys and first products thereof	1	0	0	0	0
Secondary steel for treatment, Re-processing of secondary steel into new steel	1	0	0	0	0
Precious metals	1	0	0	0	0
Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals	1	0	0	0	0
Aluminium and aluminium products	1	0	0	0	0
Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	1	0	0	0	0
Lead, zinc and tin and products thereof	1	0	0	0	0
Secondary lead for treatment, Re-processing of secondary lead into new lead	1	0	0	0	0
Copper products	1	0	0	0	0
Secondary copper for treatment, Re-processing of secondary copper into new copper	1	0	0	0	0
Other non-ferrous metal products	1	0	0	0	0
Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	1	0	0	0	0
Foundry work services	1	0	0	0	0
Fabricated metal products, except machinery and equipment (28)	1	0	0	0	0
Machinery and equipment n.e.c. (29)	1	0	0	0	0
Office machinery and computers (30)	1	0	0	0	0
Electrical machinery and apparatus n.e.c. (31)	1	0	0	0	0
Radio, television and communication equipment and apparatus (32)	1	0	0	0	0
Medical, precision and optical instruments, watches and clocks (33)	1	0	0	0	0
Motor vehicles, trailers and semi-trailers (34)	1	0	0	0	0
Other transport equipment (35)	1	0	0	0	0
Furniture; other manufactured goods n.e.c. (36)	1	0	0	0	0
Secondary raw materials	1	0	0	0	0
Bottles for treatment, Recycling of bottles by direct reuse	1	0	0	0	0
Electricity by coal	1	0	0	0	0
Electricity by gas	1	0	0	0	0
Electricity by nuclear	1	0	0	0	0
Electricity by hydro	1	0	0	0	0
Electricity by wind	1	0	0	0	0
Electricity by petroleum and other oil derivatives	1	0	0	0	0
Electricity by biomass and waste	1	0	0	0	0
Electricity by solar photovoltaic	1	0	0	0	0
Electricity by solar thermal	1	0	0	0	0
Electricity by tide, wave, ocean	1	0	0	0	0
Electricity by Geothermal	1	0	0	0	0
Electricity n.e.c.	1	0	0	0	0

Transmission services of electricity	1	0	0	0	0
Distribution and trade services of electricity	1	0	0	0	0
Coke oven gas	1	0	0	0	0
Blast Furnace Gas	1	0	0	0	0
Oxygen Steel Furnace Gas	1	0	0	0	0
Gas Works Gas	1	0	0	0	0
Biogas	1	0	0	0	0
Distribution services of gaseous fuels through mains	1	0	0	0	0
Steam and hot water supply services	1	0	0	0	0
Collected and purified water, distribution services of water (41)	1	0	0	0	0
Construction work (45)	1	0	0	0	0
Secondary construction material for treatment, Re-processing of secondary construction material into aggregates	1	0	0	0	0
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	1	0	0	0	0
Retail trade services of motor fuel	1	0	0	0	0
Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51)	1	0	0	0	0
Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)	1	0	0	0	0
Hotel and restaurant services (55)	1	0	0	0	0
Railway transportation services	1	0	0	0	0
Other land transportation services	1	0	0	0	0
Transportation services via pipelines	1	0	0	0	0
Sea and coastal water transportation services	1	0	0	0	0
Inland water transportation services	1	0	0	0	0
Air transport services (62)	1	0	0	0	0
Supporting and auxiliary transport services; travel agency services (63)	1	0	0	0	0
Post and telecommunication services (64)	1	0	0	0	0
Financial intermediation services, except insurance and pension funding services (65)	0	1	0	0	0
Insurance and pension funding services, except compulsory social security services (66)	0,7	0,3	0	0	0
Services auxiliary to financial intermediation (67)	0	1	0	0	0
Real estate services (70)	1	0	0	0,0	0
Renting services of machinery and equipment without operator and of personal and household goods (71)	1	0	0	0	0
Computer and related services (72)	1	0	0	0	0
Research and development services (73)	1	0	0	0	0
Other business services (74)	1	0	0	0	0
Public administration and defence services; compulsory social security services (75)	1	0	0	0	0
Education services (80)	0,45	0	0,36	0	0,19
Health and social work services (85)	0,12	0	0,77	0	0,115
Food waste for treatment: incineration	1	0	0	0	0
Paper waste for treatment: incineration	1	0	0	0	0
Plastic waste for treatment: incineration	1	0	0	0	0
Intert/metal waste for treatment: incineration	1	0	0	0	0
Textiles waste for treatment: incineration	1	0	0	0	0
Wood waste for treatment: incineration	1	0	0	0	0
Oil/hazardous waste for treatment: incineration	1	0	0	0	0
Food waste for treatment: biogasification and land application	1	0	0	0	0
Paper waste for treatment: biogasification and land application	1	0	0	0	0
Sewage sludge for treatment: biogasification and land application	1	0	0	0	0
Food waste for treatment: composting and land application	1	0	0	0	0
Paper and wood waste for treatment: composting and land application	1	0	0	0	0
Food waste for treatment: waste water treatment	1	0	0	0	0
Other waste for treatment: waste water treatment	1	0	0	0	0
Food waste for treatment: landfill	1	0	0	0	0
Paper for treatment: landfill	1	0	0	0	0
Plastic waste for treatment: landfill	1	0	0	0	0
Inert/metal/hazardous waste for treatment: landfill	1	0	0	0	0
Textiles waste for treatment: landfill	1	0	0	0	0
Wood waste for treatment: landfill	1	0	0	0	0
Membership organisation services n.e.c. (91)	0	0	0	0	1
Recreational, cultural and sporting services (92)	0,6	0	0	0	0,4
Other services (93)	0	0	0	0	1,0
Private households with employed persons (95)	0	0	0	1	0
Extra-territorial organizations and bodies	0	0	0	0	1

Appendix 5 - Comparison between financial aids before and after the Recovery Plan

	2020	2021	2020	2021	2020	2021	2020	2021
	MPR	MPR	MPR	MPR	CITE	MPR	CITE	MPR
Rénovation globale	- €	- €	- €	- €	- €	7 000 €	- €	3 500 €
Bonus sortie de passoire	- €	1 500 €	- €	1 500 €	- €	1 000 €	- €	500 €
BBC	- €	1 500 €	- €	1 500 €	- €	1 000 €	- €	500 €
Audit energetique	500 €	500 €	400 €	400 €	- €	300 €	- €	- €
Chaudières à granulés manuelles	10 000 €	10 000 €	8 000 €	8 000 €	2 000 €	4 000 €	- €	- €
Chaudières à granulés automatique	10 000 €	10 000 €	8 000 €	8 000 €	3 000 €	4 000 €	- €	- €
PAC géothermique	10 000 €	10 000 €	8 000 €	8 000 €	4 000 €	4 000 €	- €	- €
Chauffage solaire	8 000 €	8 000 €	6 500 €	6 500 €	3 000 €	4 000 €	- €	- €
Chaudière à buches	8 000 €	8 000 €	6 500 €	6 500 €	2 000 €	3 000 €	- €	- €
PAC a/e	4 000 €	4 000 €	3 000 €	3 000 €	2 000 €	2 000 €	- €	- €
Chauffe-eau solaire	4 000 €	4 000 €	3 000 €	3 000 €	2 000 €	2 000 €	- €	- €
Poele à à granulés	3 000 €	3 000 €	2 500 €	2 500 €	1 500 €	1 500 €	- €	- €
Poeles à bûches	2 500 €	2 500 €	2 000 €	2 000 €	1 000 €	1 000 €	- €	- €
Foyers fermés. inserts	2 000 €	2 000 €	1 200 €	1 200 €	600 €	600 €	- €	- €
Equipements solaires hybrides	2 500 €	2 500 €	2 000 €	2 000 €	1 000 €	1 000 €	- €	- €
Chaudière à gaz très haute performance	1 200 €	1 200 €	800 €	800 €	- €	- €	- €	- €
Réseau de chaleur ou de froid	1 200 €	1 200 €	800 €	800 €	400 €	400 €	- €	- €
Chauffe-eau thermodynamique	1 200 €	1 200 €	800 €	800 €	- €	400 €	- €	- €
Cuve à fioul	1 200 €	1 200 €	800 €	800 €	400 €	400 €	- €	- €
PAC a/a	- €	- €	- €	- €	- €	- €	- €	- €
Thermostat avec regulation performante	- €	- €	- €	- €	- €	- €	- €	- €
Radiateur electrique performant (remplaçant ancien)	- €	- €	- €	- €	- €	- €	- €	- €
VMC double flux	4 000 €	4 000 €	3 000 €	3 000 €	2 000 €	2 000 €	- €	- €
VMC simple flux	- €	- €	- €	- €	- €	- €	- €	- €
Isolation thermique de fenetres	100 €	100 €	80 €	80 €	40 €	40 €	- €	- €
ITE murs	75 €	75 €	60 €	60 €	50 €	40 €	25 €	15 €
Isolation toitures terrasses	100 €	75 €	75 €	60 €	50 €	40 €	25 €	15 €
ITI murs	25 €	25 €	20 €	20 €	15 €	15 €	10 €	7 €
Isolation des rampants de toiture et plafonds de combles	25 €	25 €	20 €	20 €	15 €	15 €	10 €	7 €
Protection contre le rayonnement solaire	25 €	25 €	20 €	20 €	15 €	15 €	10 €	15 €
Isolation des combles perdus	25 €	- €	20 €	- €	- €	- €	- €	- €
Isolation d'un plancher bas	- €	- €	- €	- €	- €	- €	- €	- €

Appendix 6 – Numerical results of socio-economic impacts

Change in net wealth of French General Government (BEUR)

	1P1R			1P2R			2P1R			2P2R		
	Total GG	GG-RP	GG-SA	Total GG	GG-RP	GG-SA	Total GG	GG-RP	GG-SA	Total GG	GG-RP	GG-SA
Sc1.a	1.029	-1.200	2.229	0.383	-	0.383	-0.145	-0.185	0.040	0.040	-	0.040
Sc1.b	1.029	-1.200	2.229	0.385	-	0.385	-0.145	-0.185	0.040	0.040	-	0.040
Sc1.c	1.029	-1.200	2.229	0.333	-	0.333	-0.146	-0.185	0.039	0.038	-	0.038
Sc2.a	1.029	-1.200	2.229	0.383	-	0.383	-0.145	-0.185	0.040	0.040	-	0.040
Sc2.b	1.029	-1.200	2.229	0.385	-	0.385	-0.145	-0.185	0.040	0.040	-	0.040
Sc2.c	1.029	-1.200	2.229	0.333	-	0.333	-0.146	-0.185	0.039	0.038	-	0.038
Sc3.a	1.013	-1.200	2.213	0.383	-	0.383	-0.133	-0.185	0.052	0.017	-	0.017
Sc3.b	1.013	-1.200	2.213	0.387	-	0.387	-0.133	-0.185	0.052	0.017	-	0.017
Sc3.c	1.013	-1.200	2.213	0.329	-	0.329	-0.132	-0.185	0.053	0.014	-	0.014

Change in net wealth of French Non-financial corporations (BEUR)

	1P1R	1P2R	2P1R	2P2R
Sc1.a	0.0520	0.0113	0.0410	0.0002
Sc1.b	0.0520	0.0115	0.0410	0.0002
Sc1.c	0.0520	0.0097	0.0382	0.0000
Sc2.a	0.0524	0.0127	0.0767	0.0013
Sc2.b	0.0524	0.0128	0.0767	0.0013
Sc2.c	0.0524	0.0110	0.0761	0.0013
Sc3.a	0.0581	0.0126	0.0754	0.0005
Sc3.b	0.0581	0.0128	0.0754	0.0005
Sc3.c	0.0581	0.0108	0.0722	0.0005

Change in net wealth of French Financial corporations (BEUR)

	1P1R	1P2R	2P1R	2P2R
Sc1.a	7.1E-01	1.5E-01	4.3E-03	3.3E-03
Sc1.b	7.1E-01	1.6E-01	4.3E-03	2.9E-03
Sc1.c	7.1E-01	1.3E-01	4.3E-03	1.2E-04
Sc2.a	7.2E-01	1.7E-01	1.4E-02	1.8E-02
Sc2.b	7.2E-01	1.7E-01	1.4E-02	1.8E-02
Sc2.c	7.2E-01	1.5E-01	1.4E-02	1.7E-02
Sc3.a	7.9E-01	1.7E-01	6.1E-03	7.5E-03
Sc3.b	7.9E-01	1.7E-01	6.1E-03	7.5E-03
Sc3.c	7.9E-01	1.5E-01	6.1E-03	4.5E-04

Denise TAVARES LIMA DE ALMEIDA

Methodological development of consequential Life Cycle Assessment applied to the construction sector

Résumé

Compte tenu la forte contribution du secteur de la construction et du bâtiment aux émissions globales de gaz à effet de serre, à la consommation d'énergie et à la production de déchets (entre autres), le secteur joue un rôle clé pour atteindre les objectifs de développement durable. En ce qui concerne le changement climatique, le secteur s'intègre dans des approches stratégiques visant à atteindre la neutralité carbone en 2050. Pour atteindre ces engagements ambitieux, les outils et les actions d'éco-conception appliqués à ce jour à la petite échelle devront être utilisés dans des extensions plus importantes (décisions à grande échelle). L'objectif principal de cette thèse était de proposer une méthode pour évaluer les conséquences environnementales de changements majeurs, tels que ceux issus des politiques publiques. La transition vers une économie plus respectuese de l'environnement introduit de nouvelles dynamiques dans l'économie qui ont une forte influence sur le côté financier. Pour cela, cette thèse propose une méthode basée sur des modèles stock-flux cohérents permettant de prendre en compte la distribution monétaire, avec un cadre comptable rigoureux qui permet d'identifier les changements dans les flux et les stocks. La méthode proposée a été appliquée au Plan de relance français, lancé en 2020 pour redresser l'économie française après la crise de la pandémie de Covid.

Mots clés : analyse du cycle de vie conséquentielle, secteur du bâtiment et de la construction, évaluation environnementale, modèle stock-flux cohérent, redistribution de revenue, conséquences environnementales

Résumé en anglais

Given the buildings and construction sector significant contribution to overall greenhouse gas emissions, energy consumption and waste production (among others), the sector plays a key role in achieving sustainable development goals. With respect to climate change, the sector is part of strategic approaches to achieve carbon neutrality by 2050. To achieve these ambitious commitments, eco-design tools and actions currently applied at the small scale will need to be used in larger extensions (large-scale decisions). The main objective of this thesis was to propose a method to evaluate the environmental consequences of major changes, such as those resulting from public policies. The transition to a more environmentally friendly economy introduces new dynamics in the economy that have a strong influence on the financial side. To this end, this thesis proposes a method based on consistent stock-flow models that take into account the monetary distribution, with a rigorous accounting framework that allows the identification of changes in flows and stocks. The proposed method has been applied to the French Recovery Plan, launched in 2020 to recover the French economy after the Covid pandemic crisis.

Keywords: consequential life cycle assessment, buildings and construction sector, environmental assessment, stock-flow consistent modelling, monetary distribution, environmental consequences