Transformation des systèmes de production existants et leur systèmes d'information d'entreprise (EISs) en systèmes de production cyber-physiques (CPPSs) dans le contexte de l'industrie 4.0

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ÉCOLE DOCTORALE SCIENCES DES MÉTIERS DE L'INGÉNIEUR
[Laboratoire de Conception, Fabrication, Commande – Campus de Metz]

THÈSE

présentée par: **Xuan WU**

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Spécialité: **Génie industriel**

Transformation of existing production systems with integrated enterprise information systems (EISs) into cyber physical production systems (CPPSs) in the context of Industry 4.0

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Glossary

This glossary contains the general abbreviations used in the thesis.

AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
ANN	Artificial Neural Network
API	Application Programming Interface
AutomationML	Automation Markup Language
BI	Business Intelligence
BPMN	Business Process Modeling and Notation
CNC	Computer Numeric Control
CPPS	Cyber Physical Production System
CPS	Cyber Physical System
CRM	Customer Relationship Management
DES	Discrete Event Simulation
DL	Deep Learning
DSE	Design Space Exploration
EIS	Enterprise Information System
ERP	Enterprise Resource Planning
FMS	Flexible Manufacturing System
FFT	Fast Fourier Transform
GMM	Gaussian Mixture Model
HMI	Human-Machine Interface
HMS	Holonic Manufacturing System
ICPS	Industrial Cyber Physical System
ICT	Information and Communication Technology
IoT	Internet-of-Things
IS	Information System
IT	Information Technology

IIRA	Industrial Internet Reference Architecture
LPWAN	Low Power Wide Area Network
LR	Logistic Regression
MAS	Multi-Agent System
MCDM	Multiple-Criteria Decision-Making
MES	Manufacturing Execution Systems
ML	Machine Learning
MOM	Manufacturing Operations Management
MRP	Material Requirements Planning
MQTT	MQ Telemetry Transport
MST	Manufacturing Science and Technology
KPI	Key Performance Indicator
OPC UA	Open Platform Communications – Unified Architecture
OT	Operation Technology
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
RAMI 4.0	Reference Architectural Model Industrie 4.0
RFID	Radio Frequency Identification
S-BPM	Subject-oriented Business Process Management
SCADA	Supervisory Control and Data Acquisition
SCM	Supply Chain Management
SOA	Service-Oriented Architectures
SoS	System of Systems
UML	Unified Modeling Language
VAT	Visual Assessment of Cluster Tendency
VR	Virtual Reality

Résume Étendu En Français

1 Introduction

Ce chapitre constitue l'introduction générale du sujet de recherche. Le principal problème de recherche est énoncé, à savoir, comment transformer un système de production existant avec son EISs intégré en un CPPS dans le contexte de l'industrie 4.0 ? Ce problème général est décomposé en quatre questions de recherche que nous cherchons à résoudre dans cette thèse et les objectifs de recherche sont également illustrés. Enfin, la structure de la thèse est exposée.

1.1 Contexte et motivation de la recherche

De nos jours, l'industrie manufacturière est confrontée à des tendances difficiles, telles que des produits hautement personnalisés, une complexité croissante des produits et des cycles de vie plus courts. Pour relever ces défis, la quatrième révolution industrielle, également connue sous le nom d'industrie 4.0, apparaît sur la scène en 2013. Un changement important dans l'industrie 4.0 est la fusion des mondes physique et virtuel, rendue possible en partie par les systèmes cyber-physiques (CPSs) (Kagermann et al., 2013). Cette thèse se concentre sur une application spécifique des CPSs aux environnements de production, à savoir les systèmes de production cyber-physiques (CPPSs).

L'émergence des CPPS offre de nouveaux moyens d'être compétitif dans le contexte actuel des exigences changeantes et imprévisibles du marché. Cependant, la mise en œuvre à l'échelle réelle des CPPSs dans les pratiques industrielles n'en est encore qu'à ses débuts en raison de la barrière de l'héritage (Godoy & González Pérez, 2018). En effet, lors de la mise en œuvre des CPPSs dans une usine, les systèmes hérités ne peuvent pas facilement être remplacés par de nouveaux systèmes en raison de leurs coûts d'acquisition et d'exploitation élevés et du fait qu'ils doivent généralement fonctionner pendant de nombreuses années, voire des décennies, pour être rentables. Par conséquent, la plupart des entreprises refusent une modernisation radicale de l'ensemble de leurs systèmes de production ou ne peuvent tout simplement pas prendre le risque d'abandonner un système en fonctionnement (Godoy & González Pérez, 2018). Une solution adaptée consiste à permettre aux systèmes existants d'agir dans le cadre d'un CPPS, qui non seulement préserve les fonctionnalités du système existant, mais prolonge également sa durée de vie en ajoutant de nouvelles technologies. Dans ce contexte, la transformation des systèmes existants en CPPSs devient un sujet émergent qui mérite plus d'attention et il est de notre intérêt de fournir des contributions à ce sujet.

1.2 Exposé du problème

D'après l'analyse effectuée ci-dessus, notre intérêt de recherche est la transformation des systèmes patrimoniaux en CPPS. Plus précisément, les systèmes existants auxquels nous faisons référence ici sont les systèmes de production et les systèmes d'information d'entreprise (EISs). En général, les systèmes de production fonctionnant dans l'usine sont connectés aux EISs et les EISs soutiennent les tâches de gestion, d'exploitation et de direction des systèmes de production par le biais de certains systèmes logiciels tels que la gestion de la relation client (CRM), la planification des ressources de l'entreprise (ERP) et les systèmes d'exécution de la fabrication (MES). Par conséquent, le problème de recherche abordé ici est le suivant :

Comment transformer un système de production existant avec son SIE intégré en un CPPS dans le contexte de l'industrie 4.0?

La relation entre les EISs et les CPPSs est souvent confuse. Afin de mieux comprendre notre problème de recherche, il est nécessaire d'expliquer la relation entre les EISs et les CPPSs. Les EISs sont constitués d'ordinateurs, de logiciels, de personnes, de processus et de données (Romero & Vernadat, 2016). En outre, les EISs peuvent être considérés comme des objets de traitement de l'information multidimensionnels, qui comprennent trois dimensions principales (Reix et al., 2016), i) une dimension informationnelle, c'est-à-dire que les EISs sont des représentations de l'environnement à travers un ensemble de données, ii) une dimension technologique, c'est-à-dire que les EISs sont des systèmes qui exécutent les processus de collecte, de stockage et de traitement de l'information, qui se composent de matériel et de logiciels, et iii) une dimension organisationnelle, c'est-à-dire que les EISs soutiennent les processus d'affaires et les processus décisionnels, qui nécessitent des ressources humaines et technologiques. Par conséquent, selon la définition des CPPSs que nous proposons, les EISs peuvent être considérés comme faisant partie des CPPSs.

1.3 Questions de recherche et objectifs de recherche

Le problème de recherche identifié peut être décomposé en plusieurs questions de recherche auxquelles nous cherchons à répondre dans cette thèse comme suit :

- RQ1 : Quel est l'état actuel de la recherche sur les CPPS et la transformation des systèmes existants en CPPSs ?

Jusqu'à présent, nous avons identifié le sujet de recherche de la transformation vers les CPPSs sur la base de la situation réelle dans les usines. Cependant, cette identification serait incomplète sans une analyse adéquate de la littérature. Par conséquent, nous souhaitons d'abord effectuer une revue systématique de la littérature sur les CPPSs afin de connaître l'état de la recherche et de proposer de futurs sujets de recherche. Ensuite, nous examinons en détail les méthodes de transformation des systèmes existants en CPPSs afin d'identifier les lacunes de la recherche et de positionner nos contributions.

- RQ2 : Quels éléments doivent être pris en compte pour la transformation en CPPSs ?

En raison de l'augmentation constante des liens croisés, des progrès technologiques rapides et de la multifonctionnalité, la complexité et l'opacité structurelle des CPPSs augmentent rapidement (S. Berger et al., 2021), ce qui rend difficile la connaissance des éléments constitutifs des CPPSs. Par conséquent, nous avons pour objectif de proposer un méta-modèle des CPPSs qui définit tous les éléments essentiels des CPPSs et leurs relations.

- RQ3 : Comment identifier les éléments qui doivent être ajoutés et modifiés dans les systèmes existants pour devenir des CPPSs et quelle est la séquence de transformation de ces éléments ?

D'une manière générale, la transformation peut être mise en œuvre i) soit en ajoutant de nouveaux éléments qui n'étaient pas disponibles lors de la conception initiale, comme l'ajout de nouveaux protocoles de communication ; ii) soit en modifiant les éléments existants, comme le remplacement des vieux ordinateurs par des unités de traitement plus rapides. Par conséquent, la première chose à faire est d'identifier les éléments qui doivent être ajoutés et modifiés.

Une transformation instantanée et complète de tous les éléments d'un système patrimonial en une seule étape ne peut être envisagée en raison de son impact négatif en termes d'investissements initiaux élevés, de temps de développement et de risque de pertes de production. Ainsi, la question de recherche est d'avoir une séquence de transformation standard pour indiquer quels éléments du système existant peuvent être transformés en premier et quelles sont les étapes ultérieures possibles. Afin de répondre à cette question de recherche, nous proposons une méthode qui peut faire l'analyse de l'écart entre les systèmes As-Is et les systèmes To-Be, identifier les éléments qui doivent être ajoutés et modifiés, et indiquer la séquence de transformation pour ces éléments. Afin de montrer l'utilité de la méthode, des études de cas illustrant l'utilisation de cette méthode sont développées.

- RQ4 : Comment évaluer les avantages de la solution de transformation ?

Après avoir obtenu la solution de transformation, les fabricants peuvent ne pas être confiants dans le déploiement de ces changements dans leurs systèmes existants car ils n'ont pas de preuves complètes des avantages de la transformation en raison du manque d'expérience. Par conséquent, il est important d'évaluer les avantages que cette solution de transformation apportera au système existant avant le développement réel de la solution de transformation. Afin de répondre à cette question, nous souhaitons ajouter une étape d'évaluation de la solution de transformation dans la méthode proposée.

1.4 Structure de la thèse

Cette thèse est largement basée sur les articles publiés dans des revues et des actes internationaux. Au début de chaque chapitre, les publications sur lesquelles le chapitre est basé sont listées.

Cette thèse se compose de trois parties principales : i) Le contexte de recherche dans lequel s'inscrit ce travail, y compris la définition des CPPSs, la motivation de la recherche, les questions et les objectifs de la recherche. ii) Trois contributions. Chronologiquement parlant, la première contribution de la thèse est une revue systématique de la littérature sur les CPPSs. La deuxième contribution de la thèse est un méta-modèle des CPPSs. La troisième contribution est une méthode pour la transformation d'un système de production existant avec ses EISs intégrés en un CPPS. iii) Des études de cas pour illustrer l'utilité de notre méthode proposée.

Cette thèse est structurée en six chapitres comme le montre la Figure 1.2 et le contenu de chaque chapitre est brièvement introduit comme suit :

Le chapitre 1 donne un aperçu du contexte de la recherche. Tout d'abord, nous introduisons le contexte de l'émergence des CPPSs et proposons la définition des CPPSs. Ensuite, nous présentons le problème de recherche. Après cela, nous définissons quatre questions de recherche et leurs objectifs de recherche correspondants. Enfin, nous exposons la structure de la thèse.

Le chapitre 2 étudie l'état de l'art. Tout d'abord, une revue systématique de la littérature sur les CPPSs aux stades du concept et du développement du cycle de vie de l'ingénierie des systèmes est effectuée. Un agenda de recherche est présenté pour indiquer les futures questions de recherche. Parmi les futures questions de recherche identifiées, nous nous intéressons à la transformation des systèmes existants en CPPSs. Ensuite, une revue de la littérature plus spécifique sur les méthodes de transformation des systèmes patrimoniaux en CPPSs est présentée. Enfin, les lacunes de la recherche sont analysées et les contributions de cette thèse sont positionnées.

Le chapitre 3 présente un méta-modèle des CPPSs sous la forme d'un diagramme de classe UML (Unified Modeling Language). Tout d'abord, la manière de construire le méta-modèle est illustrée. Ensuite, les classes d'objets sont illustrées, qui sont basées sur deux parties :

l'architecture 5C et les normes de modélisation d'entreprise. Enfin, les relations entre les classes d'objets sont expliquées.

Le chapitre 4 présente une méthode pour la transformation d'un système de production existant avec ses EISs intégrés en un CPPS, basée sur le méta-modèle des CPPSs. Tout d'abord, les principes d'instanciation du méta-modèle sont décrits. Ensuite, sur la base de ces principes, une méthode pour cette transformation est présentée. En conséquence, une matrice de transformation est proposée, qui est un outil utile pour comprendre l'état actuel des systèmes de production existants et visualiser quels éléments doivent être ajoutés et modifiés dans le système As-Is pour devenir des CPPSs. En outre, la solution de transformation est évaluée par des analyses quantitatives et qualitatives.

Le chapitre 5 présente des études de cas pour montrer l'utilité de la méthode proposée.

Le chapitre 6 présente la conclusion, les limites et les solutions possibles, ainsi que les perspectives sur ces contributions proposées.

2 État de l'art

L'objectif de ce chapitre est de répondre à la question de recherche #1 “quel est l'état actuel de la recherche sur les CPPSs et la transformation des systèmes existants en CPPSs ?” par le biais de revues de la littérature et de proposer nos contributions par l'analyse des lacunes de la recherche.

Tout d'abord, une revue systématique de la littérature sur le concept et le développement technique des CPPSs est effectuée, ce qui présente une vue globale de la recherche sur les CPPS et fournit un agenda de recherche contenant quatre futures questions de recherche pour tous les chercheurs dans ce domaine. Ensuite, une revue de la littérature spécifique sur les méthodes de transformation des systèmes existants en CPPSs est réalisée. Enfin, sur la base de ces deux revues de la littérature, les lacunes de la recherche sont identifiées et nos contributions sont positionnées.

2.1 Une revue systématique de la littérature sur le développement conceptuel et technique des CPPSs

Les CPPSs suscitent un intérêt croissant, mais les recherches dans ce domaine sont éparses et doivent être examinées pour comprendre leur état de développement et leur maturité. Par conséquent, le premier objectif de ce chapitre est d'effectuer une revue systématique de la littérature sur les CPPSs en fonction de leurs contributions au cycle de vie de l'ingénierie d'un tel système de production et de proposer de futures questions de recherche.

Pour réaliser l'analyse documentaire, Jan vom et al., (2009) proposent un processus circulaire itératif, comme le montre la Figure 2.1, qui a été choisi comme méthode pour réaliser une analyse documentaire systématique dans notre travail. Le champ de recherche de cette revue systématique de la littérature concerne les étapes de développement du concept et de développement de l'ingénierie au sein des CPPSs du point de vue du génie industriel. Nous avons analysé les contributions de 100 articles et les avons classées dans ces deux catégories principales : stade de développement du concept et stade de développement de l'ingénierie. Selon le modèle du cycle de vie du système (voir Figure 2.2), l'étape de développement du concept peut être divisée en trois phases : analyse des besoins, exploration du concept, définition du concept. Pour l'étape de développement de l'ingénierie, nous avons proposé d'exploiter les cinq niveaux de l'architecture classique 5C (J. Lee et al., 2015) pour examiner les articles et, par conséquent, les articles ont été classés en cinq sous-catégories : niveau de connexion intelligente, niveau de conversion des données en informations, niveau cybernétique, niveau cognitif et niveau de configuration. Le processus d'analyse documentaire est illustré à la Figure 2.3. Elle présente une ventilation de chaque étape et le nombre d'articles sélectionnés dans chaque catégorie.

Sur la base de l'analyse de la littérature effectuée dans la section précédente, une carte de recherche résumant les activités de recherche sur les CPPSs est présentée, comme le montre la Figure 2.5. Elle donne une perspective globale des principaux sujets de recherche sur les CPPSs aux stades du concept et du développement technique. Cette carte de recherche peut aider les chercheurs à examiner la maturité de l'état de développement des CPPSs et à découvrir les phases qui doivent encore être améliorées.

Selon cette carte de recherche, nous envisageons les futurs sujets de recherche potentiels suivants :

- Question de recherche #1 : intégration multidisciplinaire au stade de l'élaboration du concept.
- Question de recherche #2 : intégration technologique, informationnelle et organisationnelle au stade du développement technique.
- Question de recherche #3 : le rôle des SIE dans les CPPSs.
- Question de recherche #4 : prise en compte de la nature des friches industrielles lors de la mise en œuvre des CPPSs.

Parmi toutes ces questions de recherche, nous sommes intéressés par la question de recherche #4. Par conséquent, le deuxième objectif de ce chapitre est de comprendre l'état actuel de la recherche sur les méthodes de transformation et d'identifier les lacunes de la recherche.

2.2 Une revue de la littérature sur les méthodes de transformation des systèmes patrimoniaux en CPPSs

Les systèmes patrimoniaux englobent divers composants de la fabrication, qui sont principalement des dispositifs physiques (tels que des robots et des machines à commande numérique), des pièces à usiner, des unités de détection, des unités de calcul, des unités de contrôle, ainsi que du matériel et des logiciels informatiques. Dans ce contexte, les études existantes sur la transformation des systèmes patrimoniaux portent soit sur des méthodes de transformation pour un type spécifique de composant, soit pour l'ensemble du système patrimonial. Par conséquent, nous classons les études existantes dans ces deux catégories : i) méthodes de transformation pour des types spécifiques de composants au sein des systèmes patrimoniaux et ii) méthodes de transformation pour des systèmes patrimoniaux entiers. Une carte de recherche des méthodes de transformation est proposée, comme le montre la Figure 2.9. De nombreuses études existantes sont des propositions de concepts et les techniques de transformation sont encore dans la première phase de maturité, uniquement validées par des expériences et généralement un scénario d'étude de cas spécifique. Jusqu'à présent, la recherche dans les pratiques de l'industrie s'est concentrée sur la collecte de données à partir de divers systèmes pour créer des services supplémentaires à valeur ajoutée plutôt que sur la transformation, l'évolution, la migration ou la mise à niveau des anciens systèmes existants en CPPSs. Ainsi, l'exploration et l'amélioration de ces techniques et méthodologies sont encore nécessaires pour garantir leur applicabilité dans des cas réels. Par exemple, une plate-forme capable d'offrir les ressources technologiques et les composants fonctionnels nécessaires aux CPPSs pourrait être développée pour automatiser et normaliser le processus de transformation des systèmes existants en CPPSs.

2.3 Les lacunes de la recherche et leurs liens avec les questions de recherche

Afin de répondre aux questions de recherche, certaines leçons et inspirations peuvent être tirées des revues de la littérature susmentionnées, et les lacunes de la recherche peuvent également être identifiées afin que nos contributions puissent être positionnées en conséquence.

Dans le rappel de cette sous-section, les lacunes de la recherche et leurs liens avec les questions de recherche sont présentés.

- RQ1 : Quel est l'état actuel de la recherche sur les CPPSs et la transformation des systèmes existants en CPPSs ?

Il a été répondu à cette question dans les sections 2.1 et 2.1. Elle n'est pas répétée ici.

- RQ2 : Quels éléments doivent être pris en compte pour la transformation en CPPSs ?

Les éléments existants mentionnés dans la littérature ne sont pas complets. Pour garantir que la transformation s'adaptera à tous les nouveaux changements apportés par les CPPSs, il est nécessaire de définir tous les éléments qui doivent être pris en compte pour la transformation vers les CPPSs. À cet égard, le chapitre 3 présente un méta-modèle des CPPSs, qui définit tous les éléments essentiels des CPPSs.

- RQ3 : Comment identifier les éléments qui doivent être ajoutés et modifiés dans les systèmes existants pour devenir des CPPS et quelle est la séquence de transformation de ces éléments ?

Dans l'analyse des lacunes, les études existantes donnent rarement la séquence de transformation des éléments qui doivent être ajoutés et modifiés. Bien que quelques études aient donné la séquence de transformation, les éléments qu'elles considèrent ne sont pas complets. À cet égard, le méta-modèle de CPPS que nous proposons et qui présente les éléments complets peut être utilisé comme référence. En instanciant le méta-modèle, la séquence de transformation de ces éléments peut être obtenue. Ceci sera présenté au chapitre 4.

- RQ4 : Comment évaluer les avantages de la solution de transformation ?

La plupart des études existantes sur le sujet de la transformation s'arrêtent à la présentation de leurs concepts et seulement quelques-unes d'entre elles ont des indicateurs de performance pour évaluer les bénéfices potentiels après avoir suivi leurs solutions de transformation. Pourtant, l'évaluation de la solution de transformation avant sa mise en œuvre réelle peut éviter des risques, elle est donc très importante. Les recherches existantes se concentrent soit sur l'analyse quantitative, soit sur l'analyse qualitative, mais personne n'a suggéré une utilisation complémentaire de ces deux types d'analyse. Parce que l'analyse quantitative et l'analyse qualitative ont leurs propres avantages et inconvénients et jouent des rôles différents dans la recherche, nous proposons de les utiliser toutes les deux pour évaluer les solutions de transformation dans le chapitre 4.

3 Méta-modèle des CPPSs

L'objectif de ce chapitre est de répondre à la question de recherche #2 "quels sont les éléments à prendre en compte pour la transformation vers les CPPSs ?". Par conséquent, l'objectif de ce chapitre est de construire un méta-modèle de CPPS qui définit tous les éléments essentiels des CPPSs. En outre, les relations entre ces éléments sont également clarifiées car l'émergence des CPPSs est intrinsèquement le résultat des relations entre ces éléments.

3.1 La manière de construire le méta-modèle

Pour construire le méta-modèle des CPPSs, nous utilisons le diagramme de classes UML. Les classes d'objets du méta-modèle sont extraites de deux parties : l'architecture 5C et les normes de modélisation d'entreprise. Pour le méta-modèle proposé des CPPSs, nous n'incluons pas les attributs et les opérations (c'est-à-dire les méthodes) des classes car le méta-modèle doit être aussi générique que possible.

Les relations entre les classes d'objets sont représentées par "association" qui indique les possibilités d'échange d'informations, "agrégation" et "composition" qui indiquent les possibilités d'intégration des éléments des SIE, et "dépendance" qui indique les besoins ou les dépendances d'un élément, le client, à un autre élément, le fournisseur.

Afin d'avoir une vue d'ensemble du méta-modèle, celui-ci est présenté ici, comme le montre la Figure 3.2, où les rectangles représentent les classes d'objets et les lignes les relations entre les classes. La description détaillée du méta-modèle, y compris ses classes d'objets et les relations entre ces classes d'objets, est présentée dans les sections suivantes.

3.2 Classes d'objets dans les CPPSs et leurs relations

Sur la base de la description de chaque niveau de l'architecture 5C obtenue à partir de (J. Lee et al., 2015), un ensemble de noms-clés ont été extraits pour devenir des classes d'objets des CPPSs, comme le montre le tableau 3.1. Ensuite, la raison de la sélection des classes d'objets liées aux EISs à partir des normes de modélisation d'entreprise est également expliquée, comme le montre le tableau 3.2.

Après avoir identifié toutes les classes d'objets dans le méta-modèle, les relations entre ces classes sont établies et peuvent être divisées en trois catégories : i) relations entre les classes extraites de l'architecture 5C, ii) relations entre les classes extraites des normes de modélisation d'entreprise, et iii) relations entre les classes extraites de l'architecture 5C et celles extraites des normes de modélisation d'entreprise. La troisième catégorie de relations est décrite par trois types de relations, à savoir les relations informationnelles, technologiques et organisationnelles, liées aux trois dimensions des EISs.

À notre connaissance, il s'agit du premier méta-modèle de CPPSs proposé jusqu'à présent, qui met l'accent sur la dimension des EISs dans les CPPSs. Globalement, le méta-modèle permet de représenter une grande variété de CPPSs différents lorsque ses classes d'objets sont instanciées.

4 Une méthode pour transformer un système de production existant avec ses EISs intégrés en un CPPS

L'objectif de ce chapitre est de répondre à la question de recherche #3 "comment identifier les éléments qui doivent être ajoutés et modifiés dans les systèmes existants pour devenir des CPPSs et quelle est la séquence de transformation de ces éléments ?" et à la question de recherche #4 "comment évaluer les bénéfices de la solution de transformation ?". Tout d'abord, les principes d'instanciation du méta-modèle sont décrits. Ensuite, sur la base de ces principes d'instanciation, une méthode de transformation des systèmes patrimoniaux en CPPSs est présentée.

4.1 Principes d'instanciation du méta-modèle

Les principes d'instanciation du méta-modèle sont décrits comme suit, ce qui permet de guider le processus d'instanciation :

- Principe 1 : Les classes extraites de l'architecture 5C doivent être instanciées couche par couche du niveau C1 au niveau C5, car l'architecture 5C donne un flux de travail séquentiel pour la mise en œuvre des CPPSs. En d'autres termes, si les classes du niveau C1 ne sont pas instanciées, il est impossible d'instancier les classes du niveau C2 et il en va de même pour les autres niveaux.
- Principe 2 : A chaque niveau, les classes extraites de l'architecture 5C doivent être instanciées en premier, puis les classes extraites des normes de modélisation d'entreprise qui sont associées aux relations technologiques, informationnelles et organisationnelles à ce niveau doivent être instanciées. De cette façon, les relations technologiques sont d'abord considérées, puis les relations informationnelles et enfin les relations organisationnelles. En effet, s'il n'y a pas de relations technologiques, il est impossible d'obtenir des données/informations et d'avoir une relation informationnelle. De même, s'il n'y a pas de relations informationnelles, il est

impossible de soutenir des processus commerciaux et des prises de décision efficaces et d'avoir une relation organisationnelle.

En combinant le principe 1 et le principe 2, le processus d'instanciation commence par des classes extraites de l'architecture 5C du niveau C1 et se poursuit par des classes extraites des normes de modélisation d'entreprise qui sont associées aux relations technologiques, informationnelles et organisationnelles du niveau C1. Ensuite, cette boucle d'instanciation passe au niveau C2 et se répète jusqu'au niveau C5.

4.2 Une méthode pour la transformation vers les CPPSs

Dans cette section, sur la base des principes d'instanciation du méta-modèle, une méthode de transformation vers les CPPS est proposée comme le montre la Figure 4.1.

- Étape I : Comprendre le système tel quel

Cette étape nécessite de comprendre la composition, les fonctionnalités, les technologies utilisées, les architectures et les processus de production du système As-Is. En outre, elle permet également d'évaluer la situation du système tel qu'il est afin d'identifier les améliorations nécessaires.

- Étape II : Définir les exigences du système "To-Be".

Cette étape est une description formelle de la spécification du système To-Be. Les exigences du système peuvent alors être décomposées en fonctions de base, et chacune d'entre elles peut être remplie par des classes d'objets dédiées dans le méta-modèle.

- Étape III : Analyse des écarts par l'instanciation du méta-modèle

Le processus d'analyse des écarts réalisé en instanciant le méta-modèle est illustré à la figure 4.2. A chaque niveau, il y a quatre types d'activités de mappage (mappage des classes extraites de l'architecture 5C, mappage des classes extraites des normes de modélisation d'entreprise qui sont associées aux relations technologiques, informationnelles et organisationnelles) et une activité d'instanciation. Une chose qui mérite d'être mentionnée est qu'il n'est pas nécessaire de mettre en œuvre les cinq niveaux de l'architecture 5C car les CPPSs ont différents niveaux de maturité. Pour être plus précis, si toutes les exigences peuvent être satisfaites à un niveau donné, le processus de transformation se termine ; sinon, il passe au niveau suivant jusqu'au niveau C5. Par conséquent, à la fin de chaque niveau, il y a une activité de vérification pour voir s'il est nécessaire de passer au niveau suivant selon les exigences du système To-Be. En conséquence, une matrice de transformation est proposée, qui fournit une vue de haut niveau de ce qui devrait être amélioré (les éléments qui doivent être ajoutés et modifiés) dans le système de production actuel, comme le montre le tableau 4.1.

- Étape IV : Évaluation de la solution de transformation

Une fois la solution de transformation obtenue à l'étape III, une évaluation doit être réalisée afin de démontrer les avantages de la solution de transformation avant de la développer davantage. L'évaluation aide le fabricant à comprendre si la solution de transformation proposée est faisable ou non en fonction de son impact positif ou négatif sur le système existant. Au final, le fabricant peut décider de développer ou non cette solution de transformation en mettant en balance les avantages attendus et les obstacles réels.

Pour évaluer les avantages de la solution de transformation, des analyses quantitatives et qualitatives sont utilisées de manière complémentaire. L'analyse quantitative est réalisée sur la base des KPIs standards définis par la norme internationale ISO 22400. Nous définissons trois étapes pour réaliser l'analyse quantitative, comme le montre la Figure 4.4. Parallèlement, l'analyse qualitative est réalisée pour évaluer les avantages non mesurables de la transformation selon trois dimensions, à savoir les dimensions technologique, informationnelle et organisationnelle, comme le montre le tableau 4.7.

5 Étude de cas

L'objectif de ce chapitre est d'expliquer comment utiliser la méthode proposée au chapitre 4 et de démontrer l'efficacité et l'applicabilité générale de cette méthode. Deux scénarios d'application sont présentés : i) une étude de cas basée sur la simulation construite dans Simio, qui évite les efforts élevés de mise en œuvre dans l'usine réelle. Bien qu'il s'agisse d'une simulation hypothétique et que ses résultats n'aient aucune valeur pratique, elle est suffisante pour démontrer l'utilité de la méthode proposée. ii) une étude de cas en laboratoire, qui est une ligne d'assemblage automatisée située dans l'IUT de Nantes.

La section 5.1 clarifie chaque étape de l'application de la méthode de transformation sur le cas de simulation et la section 5.2 clarifie chaque étape de l'application de la méthode de transformation sur le cas de laboratoire. Dans les deux cas, des solutions de transformation sont proposées et les analyses quantitatives et qualitatives sont effectuées pour évaluer les bénéfices potentiels qui peuvent être obtenus de la transformation.

Les différents cas d'application ont révélé un large éventail d'applicabilité de cette méthode. Les applications de nos méthodes dans des cas de simulation et de laboratoire ouvrent la voie à d'autres tests dans des systèmes réels à l'avenir.

5.1 Cas basé sur la simulation

- Étape de transformation I : comprendre le système As-Is

Dans cette section, nous construisons une chaîne de montage dans Simio, qui se compose principalement de quatre postes de travail. Nous supposons que chaque poste de travail est équipé d'un bras robotique pour effectuer les opérations d'assemblage et que chaque bras robotique est équipé d'une caméra pour détecter le produit à manipuler. L'agencement de cette ligne d'assemblage est représenté sur la Figure 5.1.

La ligne d'assemblage fonctionne selon la séquence d'assemblage entrée précédemment jusqu'à ce que la quantité de commande prédéfinie soit atteinte. Cependant, au cours du processus de fonctionnement, on peut constater que cette ligne d'assemblage ne met pas en œuvre la connectivité de tous les éléments du réseau industriel, ce qui se traduit par l'incapacité d'obtenir des informations du milieu environnant et de répondre aux changements internes et externes.

- Étape de transformation II : définir les exigences du système To-Be.

En fonction des problèmes identifiés dans le système As-Is à l'étape I, les exigences du système To-Be sont définies :

La connectivité des produits et des postes de travail au sein d'un réseau industriel.

Dans ce cas, les produits peuvent acquérir des informations à partir de leur environnement (par exemple, les capacités et les états des postes de travail et l'état d'avancement de leur assemblage), communiquer avec les postes de travail pour le partage des données et décider des séquences d'assemblage de manière autonome, de sorte que le système To-Be puisse éviter les temps d'arrêt non planifiés des postes de travail.

- Étape de transformation III : analyse des écarts par l'instanciation du méta-modèle

Au niveau C1, conformément à la Figure 4.2, nous commençons par mettre en correspondance le système As-Is avec les classes extraites du niveau C1 de l'architecture 5C. Le résultat est présenté dans le tableau 5.1. Ensuite, ces classes d'objets sont vérifiées une par une pour voir si les exigences du système To-Be peuvent être satisfaites par de nouvelles instanciations de ces classes d'objets. Pour permettre la connectivité des produits et des postes de travail au sein du réseau industriel, les technologies RFID sont adaptées pour donner aux produits et aux postes de travail la capacité de stocker, d'acquérir et de communiquer des données. Par conséquent, les instanciations existantes de la classe "Technologie d'acquisition de données", "Technologie de stockage de données" et "Données brutes" qui sont extraites de l'architecture 5C doivent être modifiées. Selon le tableau 3.3, ce niveau ne comporte que des relations technologiques et informationnelles. Ensuite, nous mettons en correspondance le système tel qu'il est avec les classes extraites des normes de modélisation d'entreprise qui sont associées aux relations technologiques et informationnelles à ce niveau, c'est-à-dire l'instanciation de la "Capacité" comme indiqué dans le tableau 5.1. Comme les instanciations existantes des classes d'objets "Technologie d'acquisition des données" et "Technologie de stockage des données" doivent être modifiées, l'instanciation des classes "Capacité" doit être modifiée en conséquence. Puisque l'exigence du système To-Be peut être satisfaite au niveau C1, le processus d'instanciation s'arrête à ce niveau. La matrice de transformation est présentée dans le tableau 5.1.

Pour cette solution de transformation, la principale amélioration est que chaque produit et poste de travail est équipé d'étiquettes RFID et de lecteurs RFID. Par rapport au système As-Is, dans le système To-Be, les opérateurs ne participent pas au processus de décision. C'est la progression du produit le long du système d'assemblage qui conduira aux décisions.

- Étape de transformation IV : évaluation de la solution de transformation

Pour l'analyse quantitative, les valeurs de TR, UE, TE et PR vont augmenter, ce qui indique que l'efficacité de la production et la productivité du poste de travail vont augmenter. Un autre résultat est que la valeur de AE va diminuer, mais plus sa valeur est élevée, mieux c'est. AE indique dans quelle mesure la capacité planifiée du système de production est déjà utilisée et combien de capacité planifiée est encore disponible. Par conséquent, si le fabricant accorde plus d'importance à la productivité et à l'efficacité, alors cette solution de transformation est réalisable. Mais si le fabricant accorde plus d'importance à la capacité de planification du système de production, alors cette solution de transformation est irréalisable, et une nouvelle solution de transformation doit être conçue. Grâce à cette évaluation, le fabricant peut éviter les risques en déterminant à l'avance s'il doit mettre en œuvre cette solution de transformation.

Les indicateurs quantitatifs peuvent ne pas être suffisants, alors que l'analyse qualitative qui peut produire des informations approfondies et illustratives est réalisée. Selon les thèmes d'évaluation proposés dans le tableau 4.7, l'analyse qualitative est présentée dans le tableau 5.2.

Afin de valider les bénéfices apportés par la transformation du système As-Is en système To-Be, deux scénarios sont supposés comme suit :

Scénario #1 : Une panne mineure. L'un des postes de travail redondants devient indisponible en raison de quelques défaillances mineures, telles que le blocage de la file d'attente d'entrée du poste de travail.

Scénario #2 : Une panne majeure. À un moment donné, l'un des postes de travail redondants tombe en panne.

Après avoir simulé ces deux scénarios dans le système tel qu'il est et dans le système tel qu'il sera, les cinq indicateurs clés de performance (KPI) identifiés à l'étape IV sont calculés et leurs valeurs sont indiquées dans le tableau 5.3. On peut voir que dans les deux scénarios, les tendances réelles de ces KPI sont les mêmes que les résultats de l'analyse quantitative précédente, ce qui prouve la faisabilité de notre méthode.

5.2 Cas du laboratoire

- Étape de transformation I : comprendre le système As-Is

Ce cas est une ligne d'assemblage automatisée située dans l'IUT de Nantes (Cardin, 2016), comme le montre la figure 5.2. Le système As-Is a un bon degré d'automatisation pour exécuter la planification de la production et le contrôle de la qualité. L'acquisition des données est effectuée sur le réseau interne à l'aide d'un câble série. Cependant, il n'existe pas de technologie d'analyse des données pour détecter les perturbations.

- Étape de transformation II : définir les exigences du système To-Be.

Les perturbations sont principalement causées par des facteurs internes, liés aux actifs tangibles des systèmes de production, par exemple, les bris d'outils et les pannes de machines (Suwa & Sandoh, 2012) et peuvent survenir à tout moment, ce qui entrave la réalisation des objectifs de production. Par conséquent, les exigences du système To-Be sont définies comme suit :

Exigence #1: ajouter la fonction de maintenance prédictive pour détecter les perturbations.

Exigence #2 : notifier les mainteneurs pour qu'ils prennent des mesures de réparation par le biais de dispositifs IoT (par exemple, smartwatches, smartphones, lunettes intelligentes).

- Étape de transformation III : analyse des écarts par l'instanciation du méta-modèle

Au niveau C1, après les quatre activités de mapping entre le système As-Is et le méta-modèle, les instanciations des classes d'objets à ce niveau sont obtenues, comme le montrent les tableaux 5.4 et 5.5. Aucune classe d'objets ne peut être instanciée pour répondre aux exigences du système To-Be, le processus d'instanciation passe donc au niveau C2.

Au niveau C2, le processus est le même qu'au niveau C1 et aucune classe ne peut être instanciée pour répondre aux exigences du système To-Be, le processus d'instanciation passe donc au niveau C3.

Au niveau C3, nous commençons par mettre en correspondance le système As-Is avec les classes extraites de l'architecture 5C. Ensuite, ces classes d'objets sont vérifiées une par une pour voir si les exigences du système To-Be peuvent être satisfaites par de nouvelles instanciations de ces classes d'objets. L'exigence #1 concerne la fonction de maintenance prédictive. Pour permettre cela, l'instanciation de la classe d'objets "Technologie d'analyse de données" pourrait être créée. Plusieurs méthodes d'analyse de données ont été proposées pour le diagnostic et la maintenance dans la littérature, telles que la modélisation mathématique, les techniques basées sur la simulation et les outils d'IA. En outre, l'instanciation de la classe d'objets "Information" doit également être modifiée afin d'afficher les alarmes anormales de défaillances éventuelles. D'après le tableau 3.3, ce niveau ne comporte que des relations technologiques. Ensuite, nous mappons le système tel quel avec les classes extraites des normes de modélisation d'entreprise qui sont associées aux relations technologiques à ce niveau, c'est-à-dire l'instanciation de la "Capacité" comme indiqué dans le Tableau 5.4. Comme les instanciations existantes des classes d'objets "Technologie d'analyse des données" doivent être créées, l'instanciation des classes "Capacité" doit être modifiée en conséquence. Comme l'exigence #2 n'a pas encore été satisfaite, le processus de transformation passe au niveau C4.

Au niveau C4, nous commençons par mettre en correspondance le système As-Is avec les classes extraites de l'architecture 5C. Ensuite, ces classes d'objets sont vérifiées une par une pour voir si l'exigence #2 peut être satisfaite par de nouvelles instanciations de ces classes d'objets et nous constatons qu'elle pourrait être satisfaite par l'instanciation de la classe "Interface de présentation". Pour être précis, les dispositifs IoT, tels que les montres connectées, les smartphones et les outils de réalité virtuelle, peuvent être utilisés pour transmettre des recommandations de maintenance aux humains. Ensuite, nous mettons en correspondance le système As-Is avec les classes extraites des normes de modélisation d'entreprise qui sont associées aux relations technologiques à ce niveau, c'est-à-dire l'instanciation de la "Ressource". Comme l'instanciation de la classe d'objets "Interface de présentation" doit être modifiée, l'instanciation de la classe d'objets "Ressource" devra être modifiée en conséquence. Puisque toutes les exigences du To-Be peuvent être satisfaites au niveau C4, le processus d'instanciation s'arrête à ce niveau.

- Étape de transformation IV : évaluation de la solution de transformation

Pour l'analyse quantitative, les valeurs de TR, UE, TE, PR, MTBF, MTTF et MTTR vont augmenter, ce qui indique que l'efficacité de la production, la productivité du poste de travail et la fiabilité du système vont augmenter. Un autre résultat est que la valeur de AE diminuera, mais plus sa valeur est élevée, mieux c'est. AE indique dans quelle mesure la capacité planifiée du système de production est déjà utilisée et combien de capacité planifiée est encore disponible. Par conséquent, si le fabricant valorise davantage la productivité, l'efficacité et la fiabilité, alors cette solution de transformation est réalisable. Mais si le fabricant accorde plus d'importance à la capacité planifiée du système de production, alors cette solution de transformation est irréalisable et une nouvelle solution de transformation doit être conçue.

Les indicateurs quantitatifs peuvent ne pas être suffisants, alors que l'analyse qualitative qui peut produire des informations approfondies et illustratives est réalisée. Selon les thèmes d'évaluation proposés dans le tableau 4.7, l'analyse qualitative est présentée dans le tableau 5.6.

6 Conclusion

6.1 Conclusion

Dans cette thèse, nous avons formulé quatre questions de recherche. Afin de répondre à ces questions de recherche, nous avons proposé la contribution suivante :

- Contribution 1 : Une revue systématique de la littérature sur les CPPSs dans leurs phases de conception et de développement technique a été réalisée dans le chapitre 2, afin d'avoir une vision globale de l'état actuel de la recherche sur les CPPSs. Ensuite, selon cette revue de la littérature, une carte de recherche résumant les principales activités de recherche sur les CPPSs dans la littérature a été proposée, ce qui peut aider les chercheurs à examiner la maturité du statut de développement des CPPSs. Enfin, un programme de recherche comprenant plusieurs questions de recherche futures est proposé.
- Contribution 2 : le chapitre 3 propose un méta-modèle des CPPSs, qui sert de base à la méthode de transformation des systèmes existants en CPPSs. Au meilleur de nos connaissances, nous confirmons que le méta-modèle des CPPSs est complet. Bien que certaines études connexes présentent des éléments différents des CPPSs, ils sont soit plus fins ou plus abstraits que nos classes d'objets, soit simplement une partie de nos classes d'objets définies, de sorte qu'ils entrent toujours dans le champ d'application du méta-modèle.
- Contribution 3 : Une méthode de transformation des systèmes de production existants avec ses SIE intégrés en CPPSs a été proposée au chapitre 4. Cette méthode fournit un processus détaillé pour guider les gens dans la visualisation des éléments à ajouter et à modifier et pour aider le fabricant à déterminer s'il doit développer cette solution

de transformation en pesant les avantages attendus par rapport aux obstacles réels. Enfin, pour illustrer l'utilité et l'applicabilité de la méthode proposée, deux études de cas ont été présentées.

6.2 Limites et Perspective

Les limites liées à nos contributions et certaines solutions possibles sont illustrées comme suit :

- Sur la revue systématique de la littérature des CPPSs

Limitation : nous n'avons pas étudié les problèmes de l'industrie et la maturité des CPPSs dans l'entreprise.

Perspective : Enquête sur la maturité des CPPSs et les problèmes industriels.

- Sur le méta-modèle des CPPSs

Limitation : son établissement repose uniquement sur une analyse de la littérature sans fondement empirique. De plus, le méta-modèle n'a pas été vérifié et validé. .

Perspective : consulter l'expérience de l'ingénieur pour voir si le modèle doit être amélioré et vérifier l'exactitude du méta-modèle et le valider dans certains cas concrets de CPPSs.

- Sur la méthode de transformation

Limitation : Bien que l'objectif final soit de développer une méthodologie complète pour transformer les systèmes existants en CPPSs, cette thèse est pour l'instant une étude préliminaire limitée à l'étape de développement du concept. Dans la méthode proposée, le processus d'instanciation repose sur les connaissances et l'expérience des humains. En outre, l'analyse quantitative et qualitative est prise en compte dans la méthode de transformation, mais il n'existe pas de véritable méthodologie d'évaluation.

Perspective : nous allons étendre la méthode de transformation au développement de l'ingénierie avec plus de détails techniques et de modèles. Pour le processus d'instanciation, l'expérience collectée auprès des experts peut être stockée dans une bibliothèque pour être réutilisée dans de futurs projets et des outils dédiés peuvent être développés pour une identification automatique basée sur l'expérience.

- Sur l'étude de cas

Limitation : La méthode proposée n'est actuellement appliquée que dans des cas basés sur la simulation et en laboratoire, mais pas dans des cas industriels réels.

Perspective: Les travaux futurs peuvent appliquer la méthode à des cas industriels réels et essayer d'atteindre le niveau V (niveau de configuration) de l'architecture 5C où tous les avantages des CPPSs pourraient être exploités.

Hormis les perspectives d'extension de notre travail, nous proposons également quelques nouvelles questions sur les mécanismes de prise de décision comme suit.

- La transformation de la structure décisionnelle permet aux CPPSs d'avoir accès à plus de données qu'auparavant, en contournant les contraintes d'adjacence inhérentes. Par conséquent, la façon de traiter et d'exploiter ces données sera toujours l'un des principaux défis à relever. Bien que les techniques d'AI soient de plus en plus développées, leurs succès sont actuellement principalement axés sur le pronostic, la maintenance, la surveillance des processus et l'optimisation au niveau des composants. Les travaux futurs sur l'application de l'AI pourraient être étendus à la prise de décision au niveau du système, comme les stratégies à suivre, les produits à fabriquer et les marchés à cibler.
- À l'avenir, il devrait y avoir davantage de types de décisions de haut niveau dans les systèmes existants qui modifient leurs horizons de planification à des niveaux inférieurs. Par conséquent, la question de savoir quels types de décisions changeront leurs niveaux de planification pourrait faire l'objet de recherches futures.
- Bien que les décisions décentralisées prises par les composants des CPPSs augmentent la réactivité de l'ensemble du système, elles ont également des limites lorsqu'elles ne sont pas correctement coordonnées pour considérer ce qui est le mieux pour l'entreprise ou lorsqu'elles nécessitent une contribution supplémentaire de la direction pour les aligner sur les objectifs généraux de l'entreprise. Par conséquent, certaines décisions doivent être prises de manière centralisée, par exemple les décisions concernant la stratégie de l'entreprise. Cela soulève un futur sujet de recherche sur la façon de développer la capacité à gérer les droits de décision d'une manière qui trouve le juste équilibre entre la centralisation et la décentralisation afin de maximiser l'efficacité et l'efficience des processus de décision.

English Version

Chapter 1: Introduction

This chapter is based in part on the following publications (X. Wu et al., 2021):

- Wu, X., Goepp, V., Siadat, A., & Vernadat, F. (2021). A method for supporting the transformation of an existing production system with its integrated Enterprise Information Systems (EISs) into a Cyber Physical Production System (CPPS). *Computers in Industry*, 131, 103483.

Abstract

This chapter is the general introduction of the research topic. Firstly, the emergence of CPPSs is introduced through a brief review of four industrial revolutions. The way of defining CPPSs among researchers has been inconsistent. Therefore, a formal definition of CPPSs is proposed to characterize the constituent components of CPPSs. Then, the need for the transformation of legacy systems into CPPSs is identified. This research issue is further justified by analyzing the significant benefits that enterprise can obtain from such a transformation. After that, the main research problem is stated, namely, how to transform an existing production system with its integrated EIS into a CPPS in the context of Industry 4.0? This broad problem is broken down into four research questions that we aim to solve in this thesis and research objectives are also illustrated. Finally, the thesis structure is outlined.

1.1 Research context and motivation

Industrial revolutions have brought significant changes to industrial equipment and production. The first industrial revolution began in the 18th century with the arrival of steam-powered machines for mechanized production. The second industrial revolution starts in the late 19th century with the implementation of electromechanical equipment on the production line for mass production. The third industrial revolution began in 1969 with the advent of electronics and information technology for automated production. Nowadays, the manufacturing industry is facing challenging trends, such as highly customized products, increasing product complexity and shorter product lifecycles. For tackling these challenges, the fourth industrial revolution, also known as Industry 4.0, appears on the scene in 2013. A brief history of these revolutions is shown in Figure 1.1.

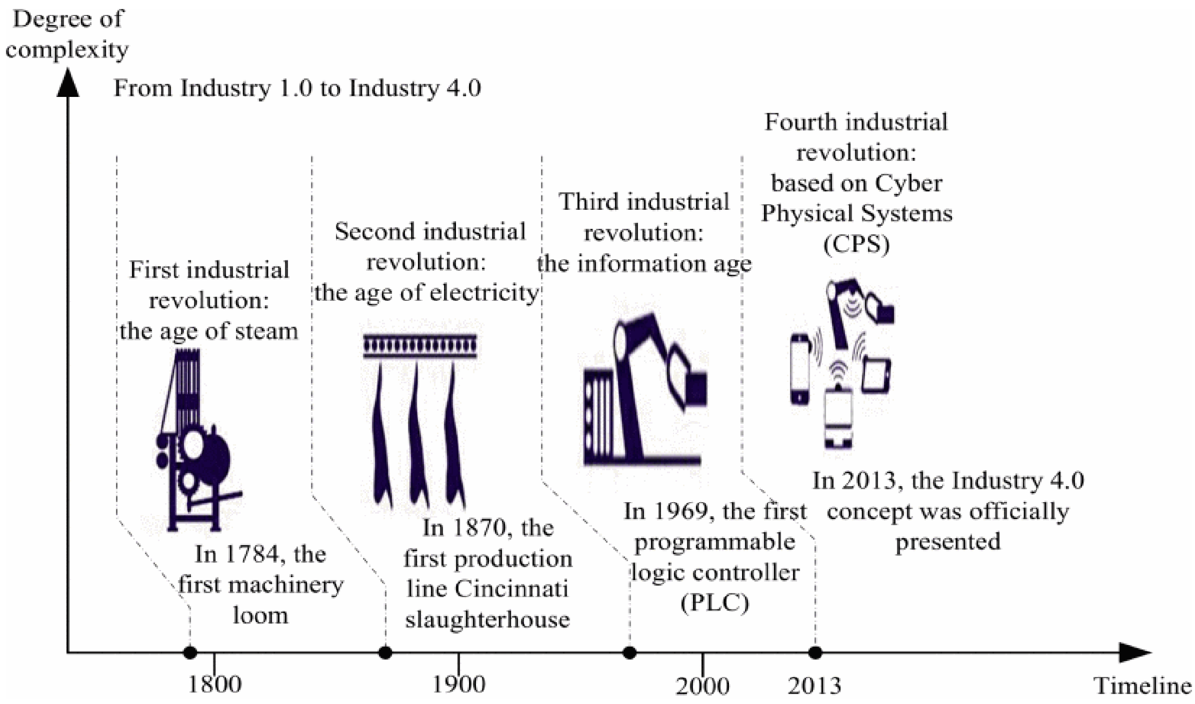

Figure 1.1 The four stages of the industrial revolution (Zhou et al., 2015)

A significant change in Industry 4.0 is the fusion of the physical and the virtual worlds, which is made possible in part by Cyber Physical Systems (CPSs) (Kagermann et al., 2013). The potential of CPS to change every aspect of life is enormous, such as transportation, healthcare, home and civil infrastructure. Concepts such as autonomous cars, robotic surgery, intelligent buildings, smart electric grid, smart manufacturing, and implanted medical devices are just some of the practical examples that have already emerged (Monostori et al., 2016). This thesis focuses on a specific application of CPSs to production environments, namely Cyber-Physical Production Systems (CPPSs).

1.1.1 The definition of CPPSs

Before we go further into the details, we should first understand what a CPPS is. There are many definitions of CPPSs, but there is no consensus on a formal definition. To sum up, there are two distinct categories of research streams on the definition of CPPSs:

- As for CPSs in general, the first research stream advocates that a CPPS is the glue (i.e. a middle-ware layer) that connects the cyber world with the physical world, as proposed by (L. Wang et al., 2015).
- The second research stream advocates that a CPPS is a System of Systems (SoS) in which cyber components work seamlessly and in synergy together with physical systems to form a whole to fulfill a common mission, as proposed by (E. A. Lee, 2008).

We adhere to the second stream that a CPSS is an SoS. A system is defined as "a complex set of interacting elements, with properties richer than the sum of its parts" (Bertalanffy, 1968). An SoS is a new system that consists of at least two loosely coupled systems that are collaborating. The broadly accepted definition of SoS is "An SoS is an assemblage of components which individually may be regarded as systems, and which possesses two additional properties: operational and managerial independence of the components" (Maier, 1996). However, although recalling what the SoS is, the existing definitions of CPPSs are still unclear on what a CPPS really is and what it should include, even the definition proposed by Monostori et al., (2016) that is widely cited in the literature. We, therefore, propose the following, more concise definition:

"A CPPS is a combination of technological agents (including smart products and smart devices), IT agents and humans, collaborating within a synergistic production environment to carry out technical, decision-making or cognitive tasks autonomously, using the best capabilities of each kind of agent involved."

In this definition, technological agents include all physical devices (such as robots and Computer Numeric Control (CNC) machines) as well as products with sensing, computation and control units, thus being able to receive and send messages and make local decisions. IT agents include hardware (such as computers) and software (such as computer programs and software packages). Humans refer to all kinds of human agents involved in the system. This formal definition stipulates the basic components (technological agents, IT agents and human) of a CPPS, as well as a relationship between these components. Furthermore, it describes the expectation of CPPSs to perform technical, decision-making or cognitive tasks autonomously.

1.1.2 Research motivation

The emergence of CPPSs is providing new ways to compete in the current context of changeable and unpredictable market requirements. However, the real-scale implementation of CPPSs in industrial practices is still in its infancy due to the legacy barrier (Godoy & González Pérez, 2018). Indeed, when implementing CPPSs in a factory, legacy systems cannot easily be replaced by new ones due to their high acquisition and operation costs and the fact that they usually have to operate for many years or even decades to be profitable. Therefore, most enterprises refuse a radical modernization of their entire production systems or simply cannot take the risk of quitting a running system (Godoy & González Pérez, 2018). A suitable solution is to enable existing systems to act as part of a CPPS, which not only preserves the functionality of the existing system, but also extends its service life by adding new technologies. In this context, the transformation of legacy systems into CPPSs becomes an emerging topic that deserves more attention.

In general, there are many reasons to trigger the transformation from legacy systems towards CPPSs, e.g., i) the legacy system is no longer cost effective, ii) the legacy system lacks the capacity to response to disturbing events, and iii), the legacy systems cannot be extended to realize new business opportunities, just to name a few.

The current and future potential benefits of this transformation to the legacy systems are enormous in many aspects, concerning technical, economic, sustainable, and social aspects (Di Carlo et al., 2021). According to (Cardin, 2019; Rudtsch et al., 2014), the main benefits that can be expected from this transformation are as follows:

- Optimization of production processes. On the one hand, CPPSs allow for better analysis of demand patterns and can optimize production processes. On the other hand, CPPSs allow for the identification of problems in production processes and can take corrective actions.
- Optimized product customization through an intelligent composition of individually suitable production systems, taking into account objectives such as product characteristics, cost, reliability, and deliverability.
- Resource-efficient production by minimizing overhead costs and flawed resource allocation.
- Human-centered production processes, where machines follow humans' speeds and instructions.

In conclusion, the transformation towards CPPSs can guarantee the enterprise's competitive advantage, organizational agility, organizational efficiency, improved quality, delightful customer experience, profitability, productivity, innovation, and environmental and social benefits. As the transformation of legacy systems into CPPSs can bring quite attractive benefits, it is our interest to provide contributions to this topic.

1.2 Problem statement

According to the analysis performed above, our research interest is the transformation of legacy systems into CPPSs. To be specific, the legacy systems referred to here are production systems and Enterprise Information Systems (EISs). In general, the production systems operating in the factory are connected to EISs and EISs support managerial, operational, and executive-level tasks of production systems through some software systems such as Customer Relationship Management (CRM), Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES). Therefore, the research problem addressed herein is:

How to transform an existing production system with its integrated EIS into a CPPS in the context of Industry 4.0?

The relationship between EISs and CPPSs is often confused. In order to better understand our research problem, it is necessary to explain the relationship between EISs and CPPSs. EISs are made of computers, software, people, processes and data (Romero & Vernadat, 2016). Furthermore, EISs can be regarded as multidimensional information processing objects, which include three main dimensions (Reix et al., 2016), i) an informational dimension, i.e., EISs are representations of the environment through a set of data, ii) a technological dimension, i.e., EISs are systems that carry out the processes of collecting, storing and processing information, which consist of hardware and software, and iii) an organizational dimension, i.e., EISs support business processes and decision-making processes, which require humans and technological resources. Therefore, according to our proposed definition of CPPSs, EISs can be considered to be included in CPPSs.

1.3 Research questions and research objectives

The identified research problem can be further broken down into several research questions that we aim to answer in this thesis as follows:

- RQ1: What is the current research status of CPPSs and the transformation of legacy systems into CPPSs?

So far, we have identified the research topic of the transformation towards CPPSs based on the real situation in factories. However, this identification would be incomplete without adequate literature analysis. Therefore, we first aim to conduct a systematic literature review of CPPSs to know their research status and to propose future research issues. Then we aim to review the transformation methods of legacy systems into CPPSs in detail for identifying research gaps and positioning our contributions.

- RQ2: Which elements need to be considered for the transformation towards CPPSs?

Owing to ever-increasing cross-linking, rapid technological advances, and multifunctionality, the complexity and structural opacity of CPPSs are rapidly increasing (S. Berger et al., 2021), which makes it difficult to know the constituent elements of CPPSs. Here, we consider the term "element" as the basic building block of a CPPS, meaning that a CPPS itself is composed of elements that are in a relation. In literature, the term "component" is sometimes used to express the same meaning as the "element" in this thesis. A common understanding of CPPS elements and their relationships is vital in order to provide guidance for the transformation of legacy systems into CPPSs. Therefore, we aim to propose a meta-model of CPPSs which defines all the essential elements of CPPSs and their relationships.

- RQ3: How to identify the elements that need to be added and modified in legacy systems for being CPPSs and what is the transformation sequence of these elements?

Generally speaking, the transformation can be implemented by i) either adding new elements that were not available when it was originally designed, such as adding new communication protocols; or ii) modifying existing elements, such as exchange of old computers by faster processing units. Therefore, to identify the elements that need to be added and modified is the first thing that needs to be addressed.

An instantly complete transformation of all the elements within a legacy system in one step cannot be considered because of its negative impact in terms of high upfront investments, development time, and risk of production losses. On the contrary, a stepwise transformation ensures low risks and immediate benefits by gradually installing new technologies in existing legacy systems. However, without a structured process to guide manufacturers on the transformation sequence of adding or modifying elements, everyone will only focus on patching their own problems and every transformation project will have to start from scratch. This will result in a loss of time, effort and cost for enterprises that want to benefit from this transformation. Thus, the research question is to have a standard transformation sequence to indicate which elements of the legacy system can be transformed first and what are possible further steps. In order to tackle this research question, we aim to propose a method that can make the gap analysis between As-Is systems and To-Be systems, identify which elements need to be added and modified, and indicate the transformation sequence for these elements. In order to show the usefulness of the method, case studies for illustrating the use of this method are developed.

- RQ4: How to evaluate the benefits of the transformation solution?

After getting the transformation solution, manufacturers may not be confident in deploying these changes in their legacy systems because they do not have complete evidence of the transformation benefits due to the lack of experience. Therefore, it is important to evaluate what benefits this transformation solution will bring to the legacy system before real development of the transformation solution. In order to answer this question, we aim to add an evaluation step to the transformation solution in the proposed method.

1.4 Thesis structure

This thesis is largely based on the papers published in journals and international proceedings. At the beginning of each chapter, the publications on which the chapter is based are listed.

This thesis consists of three main parts: i) Research context in which this work takes place, including the definition of CPPSs, research motivation, research questions and objectives. ii) Three contributions. Chronologically speaking, the first contribution of the thesis is a systematic literature review of CPPSs. The second contribution of the thesis is a meta-model of CPPSs. The third contribution is a method for the transformation of an existing production systems with its integrated EISs into a CPPS. iii) Case studies for illustrating the usefulness of our proposed method.

This thesis is structured in six chapters as shown in Figure 1.2 and the content of each chapter is briefly introduced as follows:

Chapter 1 gives an overview of the research context. Firstly, we introduce the background of the emergence of CPPSs and propose the definition of CPPSs. Then, we present the research problem. After that, we define four research questions and their corresponding research objectives. Finally, the thesis structure is outlined.

Chapter 2 studies the state of the art. Firstly, a systematic literature review of CPPS at the concept and engineering development stages of the system engineering life cycle is conducted. A research agenda is presented to indicate future research issues. Among the identified future research issues, we are interested in the transformation of legacy systems into CPPSs. Then, a more specific literature review on transformation methods of legacy systems towards CPPSs is presented. Finally, research gaps are analyzed and contributions of this thesis are positioned.

Chapter 3 presents a meta-model of CPPSs in the form of the Unified Modeling Language (UML) class diagram. Firstly, the way for building the meta-model is illustrated. Then, object classes are illustrated, which are based on two parts: the 5C architecture and enterprise modeling standards. Finally, the relationships between object classes are explained.

Chapter 4 presents a method for the transformation of an existing production system with its integrated EISs into a CPPS, based on the meta-model of CPPSs. Firstly, the instantiation principles of the meta-model are described. Then, based on these principles, a method for this transformation is presented. As a result, a transformation matrix is proposed, which is a useful tool to understand the current status of existing production systems and visualize which elements are needed to be added and modified in the As-Is system to become CPPSs. In addition, the transformation solution is evaluated through quantitative and qualitative analyses.

Chapter 5 presents case studies to show the usefulness of the proposed method.

Chapter 6 presents the conclusion, limitations and possible solutions, as well as perspectives on these proposed contributions.

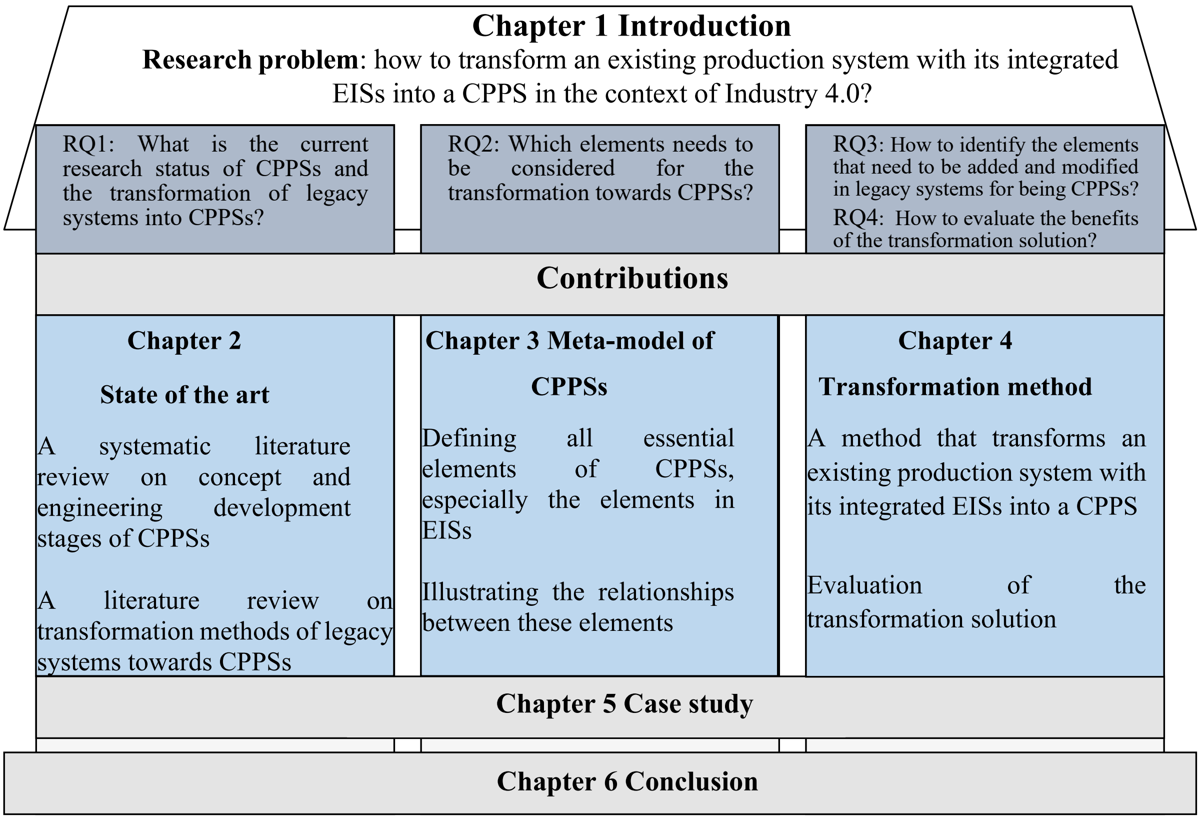

Figure 1.2 Thesis structure

Chapter 2: State of the art

This chapter is based on the following publications (X. Wu et al., 2020b) and (X. Wu et al., 2019b):

- Wu, X., Goepp, V., & Siadat, A. (2020). Concept and engineering development of cyber physical production systems : A systematic literature review. *The International Journal of Advanced Manufacturing Technology*, 111(1), 243-261.
- Wu, X., Goepp, V., & Siadat, A. (2019). Cyber Physical Production Systems : A Review of Design and Implementation Approaches. *2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 1588-1592.

Abstract

The goal of this chapter is to answer research question #1 “what is the current research status of CPPSs and the transformation of legacy systems into CPPSs?” through literature reviews and to propose our contributions through the analysis of research gaps.

Firstly, a systematic literature review on the concept and engineering development of CPPSs is conducted, which presents a global view of CPPSs research and provides a research agenda containing four future research issues for all researchers in this field. Then, a specific literature review on the transformation methods of legacy systems into CPPSs is conducted. Finally, based on these two literature reviews, research gaps are identified and our contributions are positioned.

2.1 Introduction

There is a growing interest in CPPSs, yet research in this area is scattered and needs to be reviewed for understanding their development status and maturity. Therefore, the first objective of this chapter is to perform a systematic literature review of CPPSs according to their contributions to the engineering life cycle of such production system and to propose future research issues. Among all these identified future research issues, we are interested in one of them, which is the transformation of legacy systems into CPPSs. Therefore, the second objective of this chapter is to understand the current research status of the transformation methods and to identify research gaps.

The rest of this chapter is organized as follows. Section 2.2 presents the systematic literature review of CPPSs. The literature search is limited to 2019 since this literature review has been performed in the first year of the thesis. The objective of this literature review is not to conduct an up-to-date literature analysis but rather to identify the research agenda and determine our research issues, therefore it is sufficient. Firstly, the method for carrying out this literature review is presented in Section 2.2.1. Then, in Section 2.2.2, the literature analysis is conducted. Finally, a concept map of CPPSs is outlined to present research topics at the concept and engineering development stages of CPPSs and a research agenda is presented in Section 2.2.3. Concerning one of the future research issues we identify in Section 2.2.3, namely, the transformation of legacy systems towards CPPSs, Section 2.3 presents another specific literature review on transformation methods. In line with those research questions we proposed in Chapter 1.3, Section 2.4 identifies the research gaps and positions our contributions.

2.2 A systematic literature review on concept and engineering development of CPPSs

2.2.1 Method for literature review

There are two main approaches to reviewing the literature: systematic literature reviews and narrative literature reviews. Systematic literature reviews use explicit and rigorous criteria to identify, evaluate and synthesize all the literature on a particular topic, so the bias in data extraction can be largely reduced (Cronin et al., 2008). Narrative literature reviews provide a comprehensive analysis of the current knowledge on a topic but do not describe the methods used for selecting specific sources, thus leading to difficulties in data reproduction (Cronin et al., 2008). The systematic literature review is chosen in this work because it is based on a systematic, replicable and less biased approach.

To carry out the literature review, Jan vom et al., (2009) propose an iterative circular process, which consists of 5 main steps: i) Definition of review scope, ii) Conceptualization of topic, iii) Literature search, iv) Literature analysis and synthesis, and v) Research agenda, as shown in Figure 2.1. This process is chosen as the method for conducting a systematic literature review in our work because of its iterative nature and its final result is a research agenda.

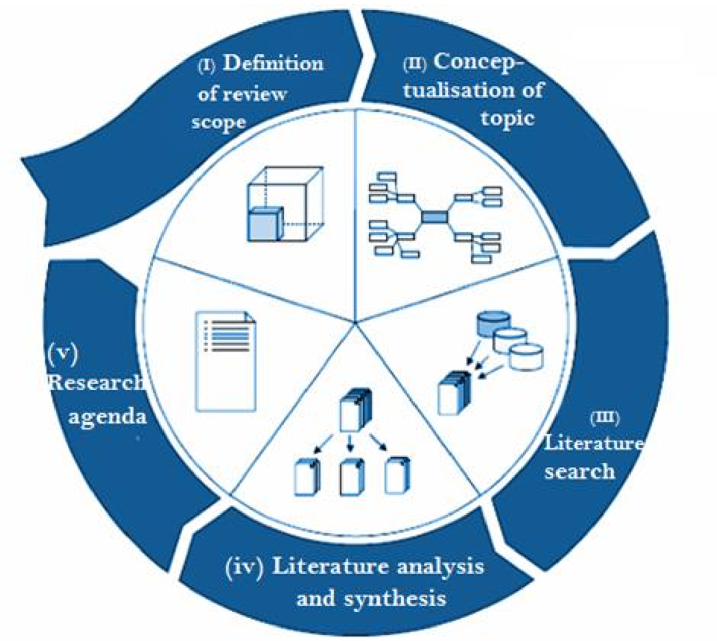

Figure 2.1 Iterative process for literature review (Jan vom et al., 2009)

The application of this process to our systematic literature review is as follows.

➢ Step I: Definition of review scope

The notion of CPPSs is very wide (Cardin, 2019) and it attracts many different research disciplines, such as industrial engineering, mechanical engineering, electrical and electronic engineering, computer science, automation and control, ergonomics as well as business and management. In this work, CPPSs are studied from the viewpoint of industrial engineering, which according to the Institute of Industrial Engineers in the USA, is "*concerned with the design, improvement, and installation of integrated systems of people, material, equipment, information, and energy to make a product or provide a service*". Therefore, industrial engineering, more than any other discipline, is concerned with the development of CPPSs in an integrated manner.

Over the last few years, there have been some literature reviews of CPPSs, as summarized in Table 2.1. It can be found that systematic literature reviews are relatively rare, with only 2 such. Moreover, most reviews focus on a specific research topic: the root of CPPSs (Monostori, 2014), integration approaches in CPPSs (Schmidt et al., 2015), international standards and patent portfolios of CPSs in manufacturing (Trappey et al., 2016), monitoring and control of ICPSs (Y. Jiang et al., 2018), programming approaches of ICPSs (U. D. Atmojo & V. Vyatkin, 2018), the classification of CPPSs applications (Cardin, 2019), production planning and scheduling in CPPSs (Rossit et al., 2019a), and the role of connectivity and control systems in CPPSs (Rojas & Rauch, 2019). Only two give a more general perspective. L. Wang et al., (2015) outline the characteristics of CPSs, representative examples and future research directions. Monostori et al., (2016) introduce the concept, characteristics, expectations, challenges and case studies of CPPSs. Therefore, one can note that existing literature reviews of CPPSs either focus on a specific research topic, or general topics including the concept, characteristics, expectations, challenges and case studies of CPPSs. However, CPPSs research is scattered and needs to be structured for understanding their maturity and to suggest future research directions for their further development. Indeed, none of the reviews investigated the development status of CPPSs according to their engineering life cycle. It is our interest to contribute with this.

According to system engineering principles (Kossiakoff et al., 2011), a system life cycle can be divided into 3 main stages: i) Concept development stage, which is the initial stage of the formulation and definition of a system concept perceived to best satisfy a valid need. The concept development stage encompasses three phases, namely, needs analysis, concept exploration, and concept definition, ii) Engineering development stage, which covers the translation of the system concept into hardware, control and software designs. The engineering development stage encompasses three phases, namely, advanced development, engineering design, and integration and evaluation, iii) Post development stage, which includes the production, deployment, operation, and support of the system throughout its useful life. The post development stage encompasses two phases, namely, production, and operation and support. The system life cycle model is shown in Figure 2.2.

The research scope of this systematic literature review is the concept development and engineering development stages within CPPSs from the viewpoint of industrial engineering.

Table 2.1 Summary of the existing literature reviews on CPPSs

Reference	**Review type**	**Focus of the literature review**
Monostori, (2014)	Narrative literature review	Description of the root, expectations and challenges of CPPSs.
Schmidt et al., (2015)	Narrative literature review	Review of the existing integration approaches and integration types in CPPSs.
L. Wang et al., (2015)	Narrative literature review	Review of the current status and the latest advancements of CPSs in manufacturing, including definitions, characteristics and applications.
Monostori et al., (2016)	Narrative literature review	Review of CPSs in manufacturing from the viewpoint of Manufacturing Science and Technology (MST), including the concept, characteristics, expectations, challenges and case studies.
Trappey et al., (2016)	Systematic literature review	Review of the international standards, and patent portfolios in CPSs.
Jiang et al., (2018)	Narrative literature review	Review of the recent advancements of Industrial Cyber Physical Systems (ICPSs) in monitoring, fault diagnosis and control approaches by data-driven realization.
U. D. Atmojo & V. Vyatkin, (2018)	Narrative literature review	Review of programming approaches for ICPSs and analysis of their capabilities.
Cardin, (2019)	Narrative literature review	Proposition of a framework for classifying CPPSs applications according to several items, including cognitive abilities, application extent, interaction with human operators, distribution of intelligence and network technologies.
Rossit et al., (2019)	Narrative literature review	Review of the most salient contributions on scheduling in CPPSs.
Rojas & Rauch, (2019)	Systematic literature review	Review of the current trends in CPPSs with a special focus on the role of connectivity and control systems in production.

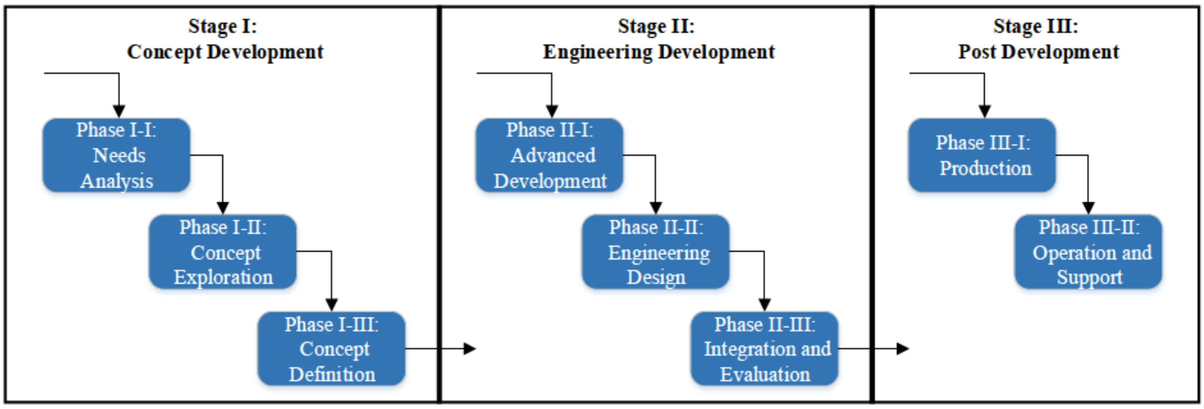

Figure 2.2 System life cycle model according to system engineering principles (Kossiakoff et al., 2011)

➢ Step II: Conceptualization of topic

This step defines the keywords used for searching articles. Since the term CPPSs means the application of CPSs in production environments, some authors may use the term ICPSs as well as the combination of "CPSs" and "manufacturing systems/production systems/smart manufacturing/intelligent manufacturing/smart factory" to illustrate the same work within the field of CPPSs. Therefore, three queries were finally identified:

- Query 1: "cyber physical production system*"
- Query 2: "industrial cyber physical system*"
- Query 3: "cyber physical system*" AND ("manufacturing system*" OR "production system*" OR "smart manufacturing" OR "intelligent manufacturing" OR "smart factory")

➢ Step III: Literature search

This step involves the search process. It is developed by first going through relevant data sources. To have access to a wide range of academic and conference publications, the ISI Web of Science database was selected. We combined the abovementioned three queries with the Boolean "OR" to search the ISI Web of Science database in "Topic" (equal to "title"+"abstract"+"keyword") until the end of 2019. A limitation to English papers was set because we intended to consider only internationally recognized work. The initial search queries resulted in a total of 1102 papers.

➢ Step IV: Literature analysis and synthesis

We imported these 1102 records that were obtained from the Web of Science into Rayyan QCRI (http://rayyan.qcri.org), a free online application that can help researchers work on systematic literature reviews. Then, we set up explicit exclusion criteria, as shown in Table 2.2, including five main exclusion criteria, together with their subsets. Once exclusion criteria have been outlined, Rayyan can help to expedite the screening work. As Rayyan is a rather simplistic interface, we used it as a platform for labeling papers, making include/exclude decisions, sharing results and collaborating reviews among co-authors. However, only the abstract/title screening can be performed automatically by Rayyan. The full-text screening has been undertaken using "manual" methods according to the exclusion reasons in Table 2.2 and checked by co-authors to reduce the subjective judgment. After the full-text screening, a total number of 100 papers were selected for the final literature analysis.

Table 2.2 Exclusion criteria

Exclusion criteria	**Criteria explanation**
Without Full Text (WFT)	There is no access to full text.
Editorial Material (EM)	Excluding the editorial material, but only journal articles and conference articles.
Non-Related (NR)	NR1: review articles. NR2: The term CPSs is not used in production environments. NR3: The term CPSs is only used as the background or future research direction. NR4: The term CPSs is only used as a short point of reference or as a collateral research topic. NR5: The topic is not related to the three phases in the concept development stage and the 5C levels.
Similar Articles (SA)	If there are two similar articles (one is a journal, and the other is a conference) written by the same authors, the conference article is excluded. If there are several similar conference articles written by the same authors, only the most recent one is included and the others are excluded.
Similar Topics (ST)	If there are several articles discussing the same topic, only the article with the highest citations is included.

Because our research scope was the concept and engineering development stage of CPPSs, we analyzed the contributions of 100 articles and categorized them into these two main categories (concept development: 46 articles, and engineering development category: 54 articles). According to the system life cycle model, the concept development stage can be further divided into three phases. Therefore, 46 articles were further categorized into three sub-categories (needs analysis: 3 articles, concept exploration: 17 articles, concept definition: 26 articles). For the engineering development stage, we proposed to exploit the five levels of the classical 5C architecture (J. Lee et al., 2015) to review articles and therefore 54 articles were further categorized into five sub-categories (smart connection level: 21 articles, data-to-information conversion level: 5 articles, cyber level: 20 articles, cognition level: 6 articles, and configuration level: 2 articles). The literature review process is shown in Figure 2.3. It presents a breakdown of each stage and the number of selected articles in each category. The corresponding literature analysis will be presented in Section 2.2.2.

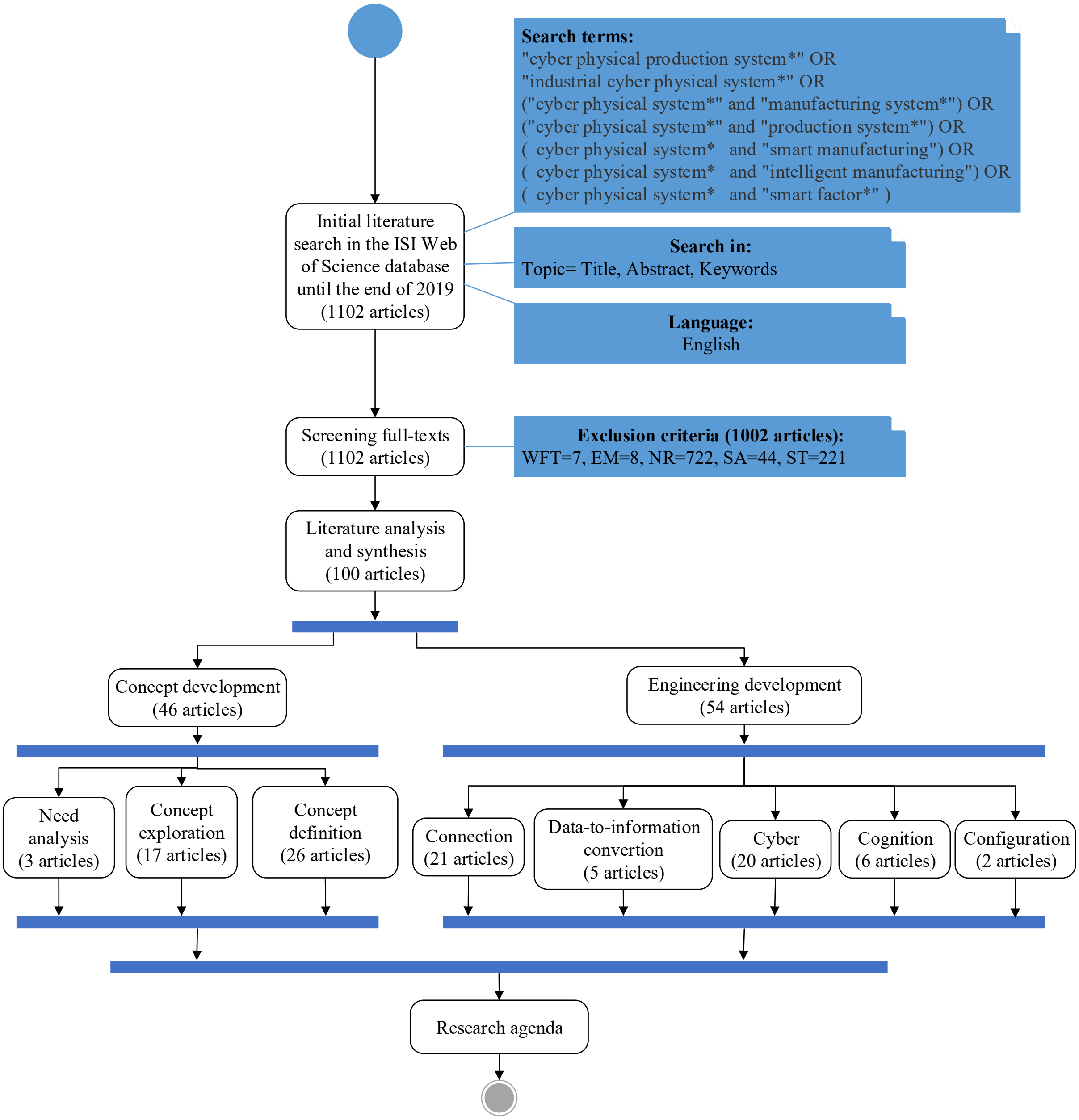

Figure 2.3 Literature review process

➢ Step V: Research agenda

Based on the literature analysis, we propose a concept map of CPPSs research in Section 2.2.3. This map is exploited to work out a research agenda of CPPSs for their industrial use.

2.2.2 Literature analysis

2.2.2.1 Concept development stage

(1) Need analysis phase

The objective of the need analysis phase is to show that there are operational needs for the development of a new system or the evolution of an existing system, and those needs can be fulfilled with affordable cost and an acceptable level of risk (Kossiakoff et al., 2011).

According to the literature screening result, research in CPPSs paid less attention to the early need analysis phase and only 3 articles were found for this phase. Firstly, compared to the traditional production systems, the degree of automation in CPPSs increases significantly and the operator's tasks shift to monitoring and supervision of CPPSs. Therefore, new requirements for the development of Human-Machine Interface (HMI) become increasingly important. Wittenberg, (2016) analyzed human-CPSs interaction requirements and mainly presented the user requirements for the usage of mobile devices, such as tablets with augmented reality and an application for data glasses. Secondly, one of the benefits that is expected from CPPSs is the improved product quality, which requires the development of quality control in CPPSs. Albers et al., (2016) defined the technical requirements for the quality control system, including requirements to controlled variable, correcting variable, controller, acquisition of process and product quality data. Thirdly, Odważny et al., (2018) analyzed and listed a set of requirements for implementing the smart factory concept, such as the access to technologies and qualified staff, the ability to organize aggregation of data of production process, the readiness to integration within a company.

(2) Concept exploration phase

The concept exploration phase translates operational requirements into system and subsystem functions, explores a range of feasible architectures, and evaluates the conformity of system concepts with operational objectives (Kossiakoff et al., 2011).

There are several standard architectures that can be adopted as conceptual architectures for CPPSs, such as RAMI 4.0 (Reference Architectural Model Industrial 4.0), IIRA (Industrial Internet Reference Architecture), IBM Industry 4.0, and NIST service-oriented smart manufacturing system architecture. RAMI 4.0 (Adolphs et al., 2015) and IIRA (Lin et al., 2015) are two of the most popular and widely recognized architectures. They put the concepts of vertical integration, horizontal integration, end-to-end engineering and life cycle together, and are regarded as promising architectures for CPPSs.

Apart from the standard architectures, many specific architectures of CPPS were also proposed in the literature. These were generally multi-layer architectures. The most popular and broadly accepted architecture was the 5C architecture of CPSs proposed by J. Lee et al., (2015). Then, Jiang (2018) proposed an 8C architecture by adding another 3C (coalition, customer, and content) facets to the 5C architecture to emphasize the horizontal integration. Authors in (Ferrer et al., 2018; C. Liu & Jiang, 2016; Rojas et al., 2017; Sanderson et al., 2018; Z. Song & Moon, 2017; Tang et al., 2018; S. Wang et al., 2018) proposed their own multi-layer architectures which basically consist of four layers or a subset of them: a physical layer, a cyber layer, a communication layer and a cloud layer. The physical layer contains all the physical elements involved in production systems. The cyber layer is the virtual representation of the physical space. The communication layer establishes the communication technologies between the physical layer and the cyber layer. The cloud layer contains cloud storage, information exchange services and various software applications. Concerning these multi-layer architectures, we found that these authors did not indicate clearly if these architectures had any mapping to the standard ones, such as RAMI 4.0 and IIRA. As RAMI 4.0 and IIRA are relatively comprehensive architectures covering various critical aspects of Industry 4.0, these specific architectures could be considered to cover a subset of the standard architectures. Therefore, further studies of the mapping relationships between these specific architectures and standard architectures are needed.

Some authors proposed architectures that took some specific design concerns of CPPSs into account, the most common one being the human factor. Pirvu et al., (2016) proposed the anthropocentric cyber-physical system architecture that integrated the physical component, the cyber component and the human component. Humans embody highly developed intelligence, such as understanding, learning and adapting, and they can provide knowledge for the design of CPPSs' architectures (Francalanza et al., 2017). Moreover, the way CPPSs and humans interact may be different, from the lowest automation (production systems just provide data to humans, who in turn make all the decisions) to full automation (CPPSs make decisions automatically and humans just supervise CPPSs) (Ansari et al., 2018; P. Fantini et al., 2016). The objective of CPPSs is not to remove humans, but to fully interact with humans. Thus, humans should play a much more important role than is the case at the moment, and further investigations of human's position in CPPSs are necessary. Apart from the human-centered design concerns, there were also many other design concerns for architectures, such as big data-centric, fog-enabled and product-centric concerns. A few notable examples are as follows.

Wang et al., (2016) proposed a cloud-based and big data-centric framework for the smart factory, which enabled transparency to supervisory control and coordinated self-organization process of manufacturing resources to achieve both high flexibility and efficiency. Wu et al., (2016) introduced a fog-enabled architecture that enabled large-scale, geographically distributed online machine and process monitoring, diagnosis, and prognosis in the context of data-driven CPPSs. Miranda et al., (2017) developed a CPPSs framework based on Sensing, Smart and Sustainable Product Development (S^3 Product). Weyer et al., (2016) presented a framework for interactions between CPS and multi-disciplinary simulation along the production life cycle.

After exploring a range of feasible architectures, it is mandatory to evaluate all architectural alternatives of the highly constrained design space defined by the systems' operational objectives. The Design Space Exploration (DSE) can be used to offer a set of high-quality implementations from which one or more solutions can be selected for later definition. J. Bakakeu et al., (2018) presented a multi-objective DSE method to evaluate architectures during the design phase and to analyze the performance of the resulting system.

(3) Concept definition phase

The aim of the concept definition phase is to select a preferred system configuration, to define functions and interactions of the component levels, to synthesize alternative technological approaches, and to conduct system simulations to confirm that the selected concept meets requirements (Kossiakoff et al., 2011). The architectures explored in the previous phase can be defined by several manufacturing paradigms including MAS (Multi-Agent System), HMS (Holonic Manufacturing System) and SOA (Service-Oriented Architecture). As CPPSs are complex, model-driven approaches are also popular for the concept definition. After defining the concept, simulation and validation approaches are necessary to confirm system requirements. These three topics are discussed as follows.

- MAS, HMS and SOA

In dynamic manufacturing environments, CPPSs need capabilities to react to disturbances and maintain system stability. These capabilities can be realized by MAS, HMS and SOA.

The term agent refers to an intelligent entity that can perform tasks autonomously (Ming et al., 1998). An agent enjoys very similar properties to a CPPS, characterized by autonomy, flexibility, robustness and adaptability. Vogel-Heuser et al., (2015) identified that the inherent characteristics of agent technologies can provide sufficient means to realize CPPSs. The interaction of multiple agents can form a decentralized system called MAS, a popular architecture for the design of distributed CPPSs. Zhang et al., (2017) proposed a CPPS for the manufacturing shop floor based on agent technology. The framework consisted of three agents, namely a smart machine agent, a self-organizing agent and a self-adaptive agent. They can allocate resources according to the production requirements and adjust when exceptions occur. Cruz Salazar et al., (2019) gathered, evaluated and compared more than twenty MAS patterns. From the analysis of these design patterns, a CPPS architecture that fulfilled requirements related to the RAMI 4.0 was identified. Agents can implement dynamic reconfiguration in a collaborative manner, but without global coordination, load-unbalance problems may occur due to the different abilities of individual agents. In this context, Li et al., (2017) proposed intelligent evaluation and control algorithms to improve load-balance with the assistance of big data feedback. Agent-based technologies have also been used as the implementation support for bio-inspired design principles, such as a bio-inspired self-organizing architecture for shop floors (Dias-Ferreira et al., 2018) and a bio-inspired self-aware health monitoring architecture for distributed industrial systems (Siafara et al., 2017). Moreover, MAS is often applied to distributed production planning and control as well as process supervision (Z. Jiang et al., 2018a; Vrabič et al., 2018).

HMS refers to a distributed control architecture consisting of a set of autonomous holons. The term holon has a dualistic character: it is a part of some bigger whole but consists of parts (Foit et al., 2017). Holons can represent a set of abstract entities in the manufacturing paradigm, including resources, orders, products and staff. MAS has been widely used as implementing framework of control models in HMS. For example, Woo et al., (2018) presented a data analytics platform for manufacturing systems that advanced the framework of HMS with the use of agent technology. Although HMS and MAS, as enablers for CPPSs, provide flexibility, autonomous and adaptability, there are still some limitations. In CPPSs, agents and holons can negotiate among themselves to cope with unexpected interrupts. As a result, the system becomes more resilient. However, this also makes the system become more complicated and difficult to manage. Therefore, a simple management method to realize the interaction is needed.

An SOA offers many benefits such as interoperability, reusability, loose-coupling and lower complexity (Niknejad et al., 2020). Various SOAs have been developed and implemented over the past decade, but they were mostly designed for software engineering applications and their application in manufacturing was still in its infancy. In order to implement the SOA in CPPSs, the manufacturing functions or applications should be encapsulated as standard services and how the services can be discovered, described, orchestrated and shared should be defined. Dai et al., (2016) introduced a knowledge-driven service orchestration engine to achieve semantic context-aware service compositions for flexible data acquisition and reconfiguration. However, interfaces to Information Systems (IS) are yet to be implemented. Lu et al., (2016) proposed a smart manufacturing architecture that integrated the entire manufacturing ecosystem, including IT (Information Technologies), OT (Operation Technologies) and supply chain logistic systems, on a single manufacturing service bus. As an extended work, Lu & Ju, (2017) further proposed a semantic modeling framework for easy development, usage and dynamic composition of cyber physical manufacturing services. Tao & Qi, (2019) proposed an IT driven service-oriented framework for promoting smart manufacturing. Recent research (Quintanilla et al., 2016) has adopted services in HMS, which gives rise to a new concept: Service-oriented Holonic Manufacturing Systems (SoHMS).

- Model-driven design approaches

The design of CPPSs is extremely complex due to its heterogeneity and integration scale. However, model-driven design will help to reduce its overall complexity. In this context, model-driven approaches were used for CPPSs by many researchers. For example, Zhang, (2018) proposed a software defined approach to model CPPSs based on Modelica Modeling Language (ModelicaML). Kannengiesser & Muller, (2018) proposed a multi-level method to model CPPSs based on semantic web standards.

The general architectures (e.g., 5C architecture and RAMI4.0) explored in the "Concept exploration" phase only give design guidelines from a high-level point of view. In this phase, they require additional formal techniques to model and specify the components involved in CPPSs. Choi & Kang, (2018) proposed to implement the 5C architecture using technologies such as PM (Process Mining), DES (Discrete Event Simulation) and VR (Virtual Reality). Contreras et al., (2017) proposed to implement RAMI 4.0 using technologies including OPC UA (Open Platform Communications – Unified Architecture), FDI (Field Device Integration) standard and AutomationML (Automation Markup Language). Pisching et al., (2018) proposed a technique derived from petri nets to define components and functionalities of a production system according to the RAMI 4.0 architecture. The top layers of RAMI 4.0, the "business" and "functional" layers, are expected to provide standard runtimes for executable business processes in the connected world (Yli-Ojanperä et al., 2019). Some work related to these two layers has already been conducted. Suri et al., (2017) proposed a model-based approach to design business strategies and the corresponding operational processes using the Business

Motivation Model (BMM) and Business Process Modeling and Notation (BPMN). Neubauer et al., (2017) proposed a Subject-oriented Process Management (S-BPM) approach to integrate business and production processes across organizational control layers. Rudtsch et al., (2014) proposed a methodology for the pattern-based development and realization of business models in CPSs.

- Simulation and validation

Simulation is important for getting an insight of CPPSs and for analyzing their behaviors under various situations. There are essentially two commonly used simulation approaches for CPPSs.

The first is the co-simulation approach, which can realize the global simulation of a coupled system by the composition of simulators. In co-simulation, the modeling is done in a distributed manner on subsystems without having the coupled system in mind (Neghina et al., 2018). The need for co-simulation of CPPSs arises because CPPSs are systems of systems and each subsystem pertains to a specialized domain. Using co-simulation, each subsystem within a larger system is simulated independently using the most suitable technique, as presented by Neghina et al., (2018) and Havard et al., (2019).

The second approach is the agent-based simulation, a promising method for simulating characteristics of complex CPPSs. For example, Novák et al., (2017) used a multi-agent paradigm to simulate CPPSs, which simplified synchronization and improved the stability of simulations.

2.2.2.2 Engineering development stage

J. Lee et al., (2015) proposed a 5C architecture for implementing CPSs, as shown in Figure 2.4. It consists of five levels, namely, smart connection, data-to-information conversion, cyber, cognition, and configuration levels. It provides a step-by-step guideline from the initial data acquisition to the final value creation. The smart connection level (level I) represents the physical space and levels II-IV represent the ‘‘pure’’ cyber space, while the configuration level (level V) realizes the feedback from the cyber space to the physical space. The 5C architecture can equally be extended to CPPSs.

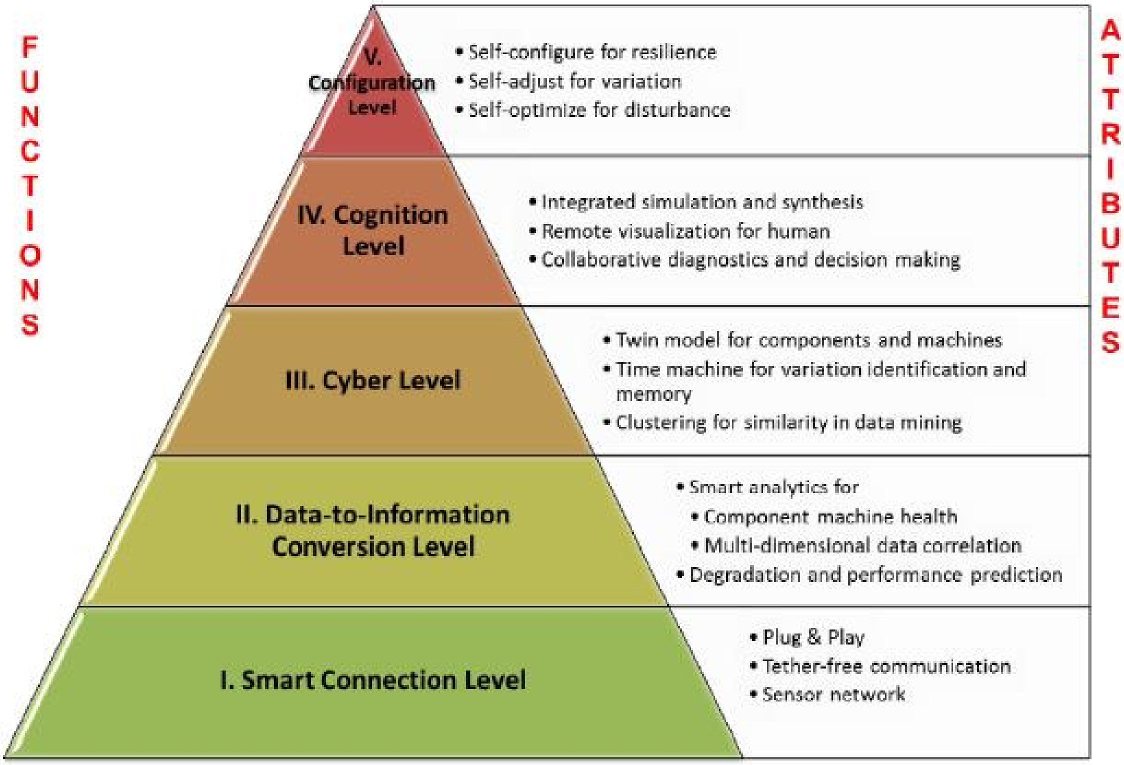

Figure 2.4 5C architecture for the implementation of CPSs (J. Lee et al., 2015)

The 5C architecture, in which the technologies are developed and validated, software and hardware subsystems are engineered and the total system is integrated into an operational environment, can be used to detail the tasks in the engineering development stage. The research focus at each level is illustrated as follows.

(1) C1: Smart connection level

This level achieves the integration between different elements in the physical space such as sensors, controllers and machine tools. Q. Liu et al., (2015) implemented an application of the vertical integration of various systems including machine tools, robots, AGVs, air-move systems and storage systems. Ding & Jiang, (2017) presented a hardware-software integrated platform for production interactions. Suri, et al., (2017) proposed a model-based approach for modular system integrations.

Because of the added connectivity in CPPSs, all devices in the production network may suffer from potential external attacks. Vargas Martínez & Vogel-Heuser, (2018) addressed this issue by introducing a reactive protection concept. Etz et al., (2018) designed an integrated safety architecture that enabled safety communication in heterogeneous production lines. Yin et al., (2017) introduced the blockchain technology to ensure the machine-to-machine communication in CPPSs. Toublanc et al., (2017) proposed a demonstrator for security on sensor/actuator networks in industrial applications.

Appropriate communication protocols and standards play an important role in the integration at this level. Therefore, much work has been done concerning this issue, including the OPC UA protocol for vertical interoperability (Hoffmann et al., 2017), ethernet standard enabled real-time processing for factory networks (Nguyen et al., 2017), MQ Telemetry Transport (MQTT) protocol for real-time data monitoring and controlling (Sonawala et al., 2017), IO-Link standard for factory automation communication (Heynicke et al., 2018), AutomationML standard for data exchange (Berardinelli et al., 2016), oneM2M standard for semantic interoperability (Willner et al., 2017), Low Power Wide Area Network (LPWAN) applied to the sensor network for data transmission (D.-Y. Kim et al., 2017), a middleware for data aggregation between the shop floor and IS (Zarte et al., 2016), a CPPS gateway for integrating high availability communication interfaces (Urbina et al., 2017).

Since different elements in CPPSs are able to generate a large amount of data about the ongoing production processes, big data acquisition and storage approaches are required. Marini & Bianchini, (2016) described a data-as-a-service approach to deal with big data storage. Silva et al., (2017) presented a sensor integration solution that allows for automatic data acquisition. Dai et al., (2017) adopted a service-oriented data acquisition approach. Ding et al., (2018) proposed a Radio Frequency Identification (RFID) enabled manufacturing system to collect real-time production and transportation data. In order to achieve reliable and accurate data acquisition, Deng et al., (2018) proposed data cleansing algorithms for energy-saving.

(2) C2: Data-to-information conversion level

With the increasing connections of systems, enormous amounts of data will be constantly generated. Considering the increasing amount and complexity of data, appropriate tools and methodologies, such as data mining, are required to extract meaningful data (X. Xu & Hua, 2017; Wiemer et al., 2019). Different types of data processing methods, including clustering, decision trees and Bayesian statistics, were reviewed by L. D. Xu & Duan, (2019).

In the era of big data, data-driven manufacturing provides a full range of value-added services to enterprises, including smart design, smart planning and process optimization, material distribution and tracking, manufacturing process monitoring, product quality control and smart equipment maintenance (F. Tao, Qi, et al., 2018). Some examples are as follows. Wan et al., (2017) implemented a manufacturing big data solution for active preventive maintenance. Niggemann & Frey, (2015) outlined a data-driven approach to extract the most relevant data for anomaly detection and diagnosis. Kißkalt et al., (2018) described a machine learning approach for data-driven process and condition monitoring systems. J. Lee et al., (2018) implemented a CPPS to predict the quality of metal casting by several machine learning algorithms such as decision trees, random forest, artificial neural networks and support vector machines.

(3) C3: Cyber level

This level is a central data hub, which aggregates all the meaningful data from various sources to form a cyber space (J. Lee et al., 2015). Some researchers noticed the importance of resource sharing and management, and a series of such research topics have been proposed, such as resource sharing (Freitag et al., 2015) as well as resources definition, matching and management (Z. Jiang et al., 2018b; Mladineo et al., 2018; Wan et al., 2018).

Having massive amounts of data gathered, specific analytics have to be used to extract useful information (J. Lee et al., 2015). For example, the self-comparative information of machines is available for evolution. Haubeck et al., (2017) proposed to enhance evolution at the cyber level of CPPSs by using the inherent experience of machines that were augmented by additional experience of similar machines at potentially remote locations.

Due to the increasing connectivity to external networks, CPPSs are easily targeted by cyber-attacks. Therefore, the cyber security of CPPSs is an important research topic. Security techniques can be grouped into (i) monitoring and detecting. For example, a cross-layer anomaly detection approach by fusing evidence from a wide range of monitored parameters was presented by Sandor et al., (2017), (ii) defense techniques. For example, Khalid et al., (2018) proposed a security mechanism based on a two-pronged strategy for a collaborative robotic cyber-physical system.

The digital twin, which builds the link between the physical and the cyber worlds, is a very important research focus. Many researchers studied the technologies, tools and approaches for realizing digital twins, such as cloud computing technologies (Qi et al., 2018), virtual engineering tools (Konstantinov et al., 2017), multi-modal data acquisition approaches (Uhlemann, Lehmann, et al., 2017), resource virtualization technologies (Lu & Xu, 2018), open source approaches (Damjanovic-Behrendt & Behrendt, 2019), a digital twin-based CPPSs framework (Ding et al., 2019). The benefits of digital twins of real-time data acquisition and the subsequent simulation-based data processing were demonstrated by Uhlemann, Schock, et al., (2017). Digital twins cover all life cycle activities and processes from design, production, utilization to service (F. Tao, Cheng, et al., 2018). Therefore, a specific digital twin application can be assigned to multiple purposes:

- Design, simulation and verification: Q. Liu et al., (2019) presented a digital twin-driven methodology for rapid individualized design of manufacturing systems and discussed how the digital twin was applied in simulating and verifying system behaviors.
- Production planning and control: M. Kück et al., (2016) proposed a digital twin-driven simulation-based approach for the adaptive scheduling and control of dynamic manufacturing systems. In addition, an approach for developing a human digital twin, which took part in decentralized production planning and control was described by Graessler & Poehler, (2017).
- Monitoring and prediction: digital twins can be used for continuous monitoring to discover undesirable situations in a proactive manner and to predict outcomes based on real-time data (J. Wang et al., 2019).
- Management and optimization: in the design phase, digital twins can be used to optimize design schemes and improve design models. In the production phase, the whole manufacturing process can be controlled and optimized by digital twins in real-time (Zhuang et al., 2018).

Existing digital twin applications are mainly developed for simulation, anomalies monitoring and prediction purposes, and very few of them take autonomous feedback control from a cyber object to a physical object into account. Real digital twins should have both physical-to-cyber data exchange and cyber-to-physical data exchange. Therefore, more research efforts should be made to implement bidirectional automated data exchange between physical objects and cyber objects.

(4) C4: Cognition level

Since abundant information is available, the cognition level can generate comprehensive knowledge of CPPSs. Appropriate presentation tools are needed to transfer knowledge to humans. Zinnikus et al., (2017) presented a 3D visualization tool to help humans repair occurring faults. Fischer et al., (2017) presented a speech interaction system that provided maintenance information to workers over wireless headphones and microphones. Constantinescu et al., (2015) presented human-system interfaces to proactively provide the required information at the right time based on the users' context during the modeling and simulation activity.

To support correct and efficient decision-making, relevant knowledge should be provided to humans depending on the current context. Hoos et al., (2017) addressed this problem by introducing the concept of a decision packet that enabled operators to find problem-solving knowledge. Rahm et al., (2018) provided a self-learning assistance system for operators, technicians and maintenance teams to enhance their fault diagnosis and correction capabilities. Galaske & Anderl, (2016) presented simulation-based decision support for the disruption management process in a resilient CPPS. By evaluating each disruption event scenario, the best strategy, including the expected impact on production processes, can be recommended to decision-makers.

(5) C5: Configuration level

At this level, the decisions made at the cognition level will be applied to the physical space. This can achieve resilience control and adjustment, especially the self-X capabilities. For example, Grundstein et al., (2017) presented an autonomous production control method for manufacturing processes, which acted autonomously and kept the resilience of CPPSs. Scholze & Barata, (2016) presented a context awareness approach for self-optimization of flexible manufacturing processes. This level has the highest requirements of self-X capabilities. Research efforts towards this level are relatively rare.

2.2.3 Research map and research agenda

Based on the literature analysis performed in the previous section, a research map summarizing the research activities in CPPSs is presented, as shown in Figure 2.5. It gives a holistic perspective on the main research topics of CPPSs at the concept and engineering development stages. This research map can help researchers to examine the maturity of the development status of CPPSs and to discover which phases require further improvement.

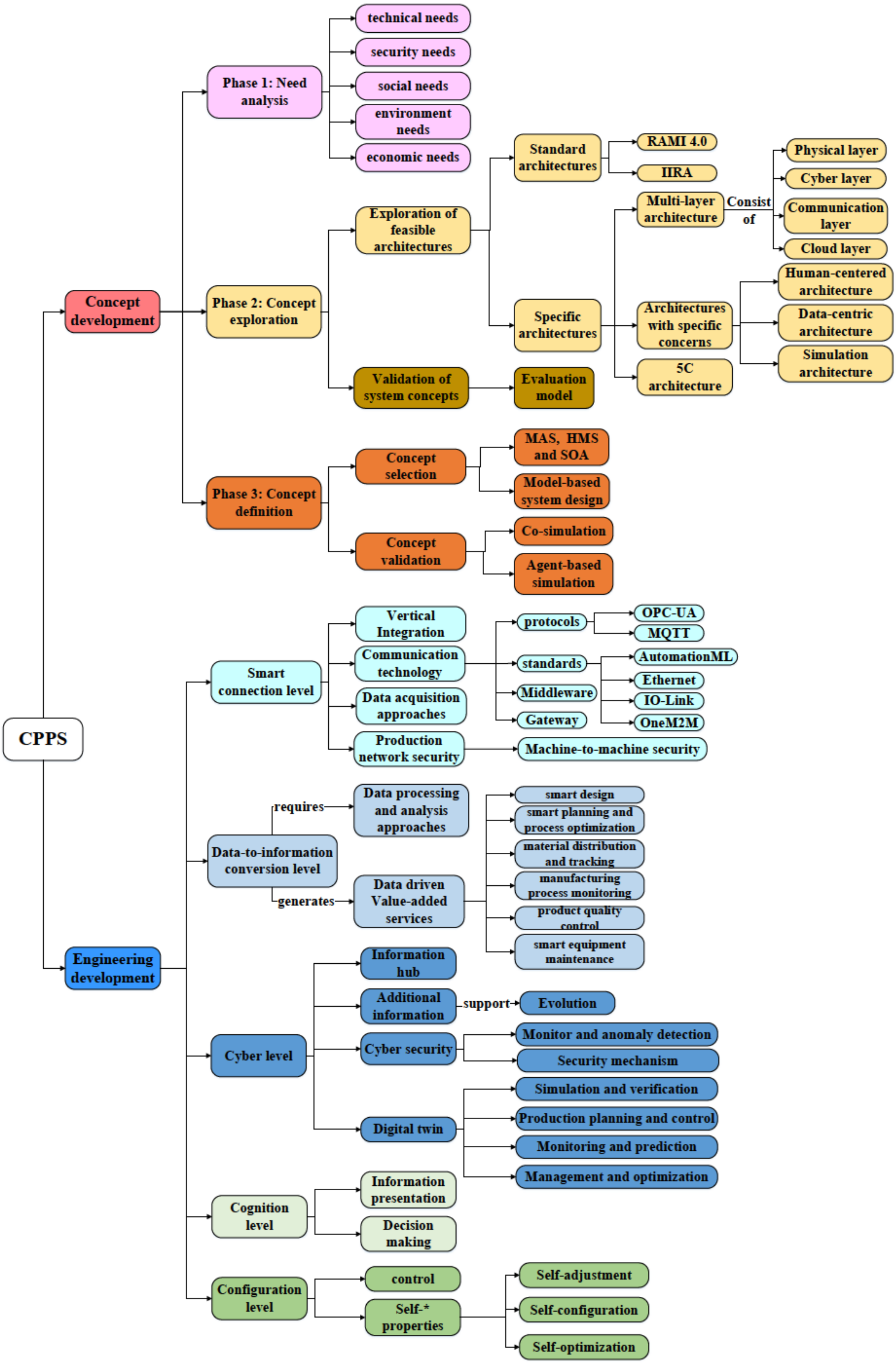

Figure 2.5 A research map for CPPSs

According to this research map, we envision the following potential future research issues:

- Research issue #1: multidisciplinary integration at the concept development stage

Different communities (e.g., mechanical engineers, electrical engineers, software engineers, etc.) develop CPPSs concept from their specific domain knowledge. Therefore, specified interactions and interfaces between various disciplines and involved components are needed for mutual communication understanding. This gives rise to the issue of multidisciplinary integration in CPPSs.

In the “Needs Analysis” phase, the complexity of systems leaves needs fragmented among different disciplines and sometimes the needs are conflict, unstable or not fully defined. Therefore, in future work, a way has to be found for the collaborative and consistent description of needs between different stakeholders, as well as their validation and evolution. This could be addressed by a common standard or natural language, such as natural language processing (Wiesner et al., 2014) and model-based graphic language (Borgne et al., 2016). In this way, domain barriers can be greatly reduced or fully removed.

In the “Concept Exploration” phase, an integrated architecture is needed so that designers take all engineering disciplines into consideration simultaneously. The RAMI 4.0 provides such a holistic view of all the important aspects that are needed by different stakeholders. Therefore, in future work, in order that the research community does not confuse themselves and users by multiple architectures, architectures based on RAMI 4.0 should be built.

In the “Concept Definition” phase, many studies have instantiated the general architectures according to some specific technologies, and the most popular being MAS, HMS and SOA. However, one can note that these technologies have already been developed in the past decades and addressed the same objectives as CPPSs. The novelty of CPPSs lies not in establishing new technologies but in combining existing technologies, such as MAS, SOA, Internet-of-things (IoT), cloud computing and big data. Therefore, the future research focus is to connect the dots between the existing isolated technologies as they are not consistently aggregated, which requires a multidisciplinary system integration across lifecycle phases.

- Research issue #2: technological, informational and organizational integration at the engineering development stage

Technological integration uses interoperability technologies or interfaces to perform data collection, storing and processing. Informational integration deals with the exchange of data and information between EISs software packages and physical components. Organizational integration deals with the way CPPSs impact business processes and decision-making.

At the C1 level, the diversity of systems and communication technologies is the reason for the high complexity and configuration difficulties of technological integration. Standardization and semantic interoperability could be useful solutions. At the C2 and C3 levels, CPPSs can access a large amount of information that has not been available previously, which brings difficulties to informational integration. Therefore, how to extract useful information that contributes to the overall performance of the organization should be investigated. At the C4 and C5 levels, the future work should study how to decentralize part of the decisions that are currently made in EISs to CPPSs components (such as smart machines and smart products), which will ensure that decisions can be made at the right level quickly.

- Research issue #3: the role of EISs in CPPSs

Some changes brought by CPPSs, such as decentralization, cloud computing and advanced analysis, create new challenges to EISs, which requires studying the role of EISs in CPPSs. Currently, there have been some studies exploring the role of MES in CPPSs. For example, Rossit et al., (2018) claim that current MES, which take care of scheduling and dispatching work orders, will be absorbed by CPPSs. ZVEI, (2017) working group indicate that functions of MES will shift away from simple execution management towards comprehensive coverage of all Manufacturing Operations Management (MOM) activities. However, this research issue is still in its infancy and deserves more attention and in-depth research.

- Research issue #4: consideration of the brownfield character when implementing CPPSs

The term “brownfield” refers to the creation on top of legacy systems rather than starting from scratch (Etz et al., 2020). The construction of CPPS from scratch is rather an exception than a standard because of the economic factors (Lass & Gronau, 2020). Therefore, the typical implementation of CPPS is to be seen as a brownfield scenario. However, existing research activities are mainly about the development of new technologies and components for CPPSs, not the brownfield situation for CPPSs.

At the concept development stage, although many theoretical concepts (such as RAMI 4.0 and MAS) provide generic structuring frameworks or guidelines for implementing CPPSs, they do not deal with brownfield implementations. For example, although RAMI 4.0 includes concepts and standards for Industry 4.0 implementation, it does not suggest a way to transform old equipment into modern CPSs. At the engineering development stage, a main research focus until now has been collecting data from various systems and processing data to create additional value-added services rather than transforming existing legacy systems for CPPSs compliance. Therefore, in future work, the implementation of CPPSs should consider the brownfield character.

Among all these research issues, we are interested in research issue #4. Transformation topics that support industries in adopting new technologies have been already considered in this systematic literature review of CPPSs, however, they are not designed for brownfield situations towards CPPS. Therefore, a detailed literature review on this research issue is presented in the next section.

2.3 A literature review on transformation methods of legacy systems into CPPSs

We set up our literature search using the combination of transformation-related queries (including "transformation", "evolution", "transition", "migration" and "retrofit") and CPPSs-related queries (including "industry 4.0", "smart factory" OR "smart manufacturing", "cyber physical systems" and "cyber physical production systems"). We only screen articles that focus on the transformation of legacy systems into CPPSs. Therefore, articles in which the system is technologically upgraded but do not aim to transform to CPPSs are not within the scope of this literature review. After the screening process, it can be found that there are not many articles on the transformation methods, only 19 articles, so it is an emerging topic that deserves more attention.

Legacy systems subsume various components of manufacturing, which are primarily physical devices (such as robots and CNC machines), workpieces, sensing units, computation units, control units, as well as IT hardware and software. In this context, existing studies on the transformation of legacy systems are either transformation methods for a specific type of component, or for the entire legacy system. Therefore, we categorize existing studies into these two categories: i) transformation methods for specific types of components within legacy systems and ii) transformation methods for entire legacy systems.

2.3.1 Transformation methods of specific types of components

Many legacy systems follow the ANSI/ISA-95, (2013) standard to specify their hierarchal control levels, as shown in Figure 2.6.

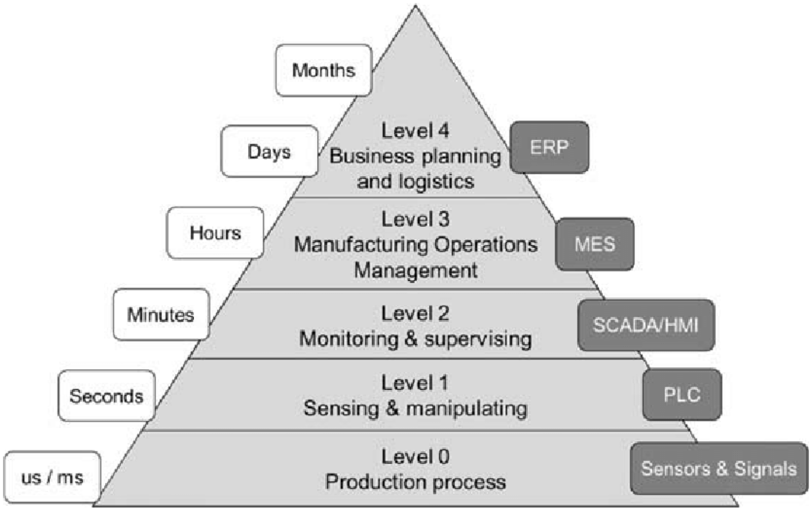

Figure 2.6 The automation pyramid (ANSI/ISA-95, 2013)

According to the ANSI/ISA 95 hierarchy, we categorize the existing studies of specific types of components into three main categories: i) field devices at Level 0, ii) process control and supervision systems at Level 1 and Level 2, iii) enterprise management and manufacturing execution systems at Level 3 and Level 4. The detailed literature analysis in these three categories is as follows.

(1) Field devices

The bottom level of ISA 95 contains field devices for sensing and manipulating the production process. In the legacy system, not all industrial devices are CPPSs-ready. IoT technologies can be seen as a major enabler to transform legacy devices to become CPPS compliant because they provide an opportunity to connect various devices and deploy intelligent analytics services based on data captured from these devices. Therefore, the integration of these legacy devices into IoT applications is of interest to many researchers. The following studies present the methods for transforming legacy devices to IoT compliant devices.

Arjoni et al., (2017) proposed retrofit techniques to allow old automation and mechatronic components such as robotic arms and CNC machines to be reused in Industry 4.0 by modifying the machinery communication interfaces. R. G. Lins et al., (2017) proposed a method to retrofit existing CNC machines based on IoT architecture, which depicted in detail the functional requirements, design parameters, data model and system architecture. Godoy & González Pérez, (2018) presented an approach to establish effective communication between the sensors/actuators network and a supervisory system within a legacy manufacturing system. Mourtzis et al., (2018) presented a methodology to transform legacy CNC machine tools into the Machine Shop 4.0 through the OPC- UA standard. Botcha et al., (2018) presented an initial implementation to transform a machine tool with a smart sensor wrapper to enable real-time process monitoring. Lima et al., (2019) presented a machine retrofit using an energy measurement industrial sensor and an IoT gateway to provide connectivity to machines. Lucke et al., (2019) presented an approach to retrofit legacy machines with sensors by using a service-oriented architecture. Ooi et al., (2020) proposed a retrofit approach that attaches wireless vibration sensors onto legacy manufacturing machines to capture the vibration of the machines. Etz et al., (2020) presented a retrofit solution to implement an OPC UA gateway for a legacy robot system in order to allow seamless communication across machines. T. Lins & Oliveira, (2020) proposed the process of transforming old devices into CPPSs, using IoT devices, communication networks and applications. To sum up, transforming legacy devices to IoT-enabled devices was realized mainly through sensors, communication standards, protocols and interfaces.

(2) Process control and supervision systems

The middle level of ISA 95 contains both process controllers that run control algorithms and interact with control loops as well as supervisory control and data acquisition (SCADA) systems that supervise the operation of control loops. The following studies present the transformation methods of legacy process control and supervision systems. Bjetak et al., (2019) presented a use case for enhancing awareness features of a Programmable Logic Controller (PLC) by using low-cost IoT equipment. Khan et al., (2020) proposed an approach to seamlessly and securely migrate legacy industrial SCADA systems to the cloud.

To summarize, the transformation towards CPPSs has put additional requirements on the traditional process control systems that are often operated locally inside factories, such as more service-oriented control functions and connectivity to the cloud while meeting the real-time requirements. To meet these requirements, the transformation of process control and supervision systems was realized mainly through two solutions: i) implement control functions by IoT-compliant components, and ii) implement control functions in a cloud.

(3) Enterprise management and manufacturing execution systems

The upper level of ISA 95 manages manufacturing operations, business planning and logistics by ERP and MES. At this level, CPPSs are expected to interconnect everything across the production system and seamlessly integrate isolated systems and business processes to eliminate the traditional data and information silos, which is often achieved through the cloud computing in research studies. Cloud computing is enabling a new way of delivering industrial software solutions and providing services and insights to customers by migrating non-physical functions and services into the cloud (Breivold, 2020). Therefore, existing studies of transforming the enterprise management and manufacturing execution system are to offer enterprise applications as cloud-based services. For example, Gunka et al., (2013) described an iterative approach to migrate an existing application to the cloud by using model-based techniques to develop appropriate deployment architectures and by selecting suitable cloud providers. To summarize, a common approach at this level is to migrate industrial software applications to the cloud and to offer common functions as cloud-based services.

2.3.2 Transformation methods of entire legacy systems

Transformation methods reviewed in Section 2.3.1 show a restriction on a specific type of components, which limits the reutilization of the same process in different components. However, identifying common points of the transformation, either technologies needed for CPPSs or general guidelines and processes, is a way to facilitate the transformation. Therefore, this section presents the general transformation methods for the entire legacy systems, which can be further categorized into two subcategories: the transformation methods that focus on technologies installed and development details, and the general transformation process described at a high-level manner in the execution of the process.

(1) Transformation methods with specified technologies

Pessoa et al., (2018) proposed an approach to connect dispersed legacy production systems with different communication protocols to the cloud-based IoT platform. Lass & Gronau, (2020) proposed a concept of a CPS component, including flexible software architecture and hardware, which allows to retrofit the demanded properties and equip a production unit with CPS capabilities. To sum up, these transformation methods described details of the technical solutions for the entire legacy system and provided proofs of concept.

(2) General transformation processes

Ehrlich et al., (2015) proposed a migration process of traditional production lines, which consisted of four consecutive phases: interviews, questionnaires, requirements analysis, investigation. The main goal of the first phase is to know the actual state and the desired target state of the existing system in order to understand the whole problem and the given tasks. The second phase is to collect all relevant information about the existing system, such as technologies, functionalities, tools and software. The third phase covers the definition of the requirements and use cases for the target state of the system based on sophisticated analysis. The final phase is to develop a suitable solution consisting of well-chosen technologies and components which fit the needs of the target state of the system.

Calà et al., (2017) defined a general migration process, which consisted of five phases: preparation, options investigation, design, implementation, and deployment, as shown in Figure 2.7. The purpose of the first phase is to analyze the existing system and define the target system. In the second phase, possible solutions are collected and assessed. This solution option is then detailed within the "design" phase, including the tasks necessary to implement according to the migration strategy, i.e., Phased Introduction, Parallel Systems or Big Bang. Moreover, in this phase, the viability of the designed solution is also tested, ensuring that the next phase is only initiated when viable planning has been met. In the "implementation" phase, the selected solution option is realized and verified. Finally, in the "deployment" phase, the new system is installed and further validated, in a real-environment state. If the results do not match with the expected benefits, the user can repeat the previous phases and select a different option or re-define the goal of the migration. The process is repeated for each migration step.

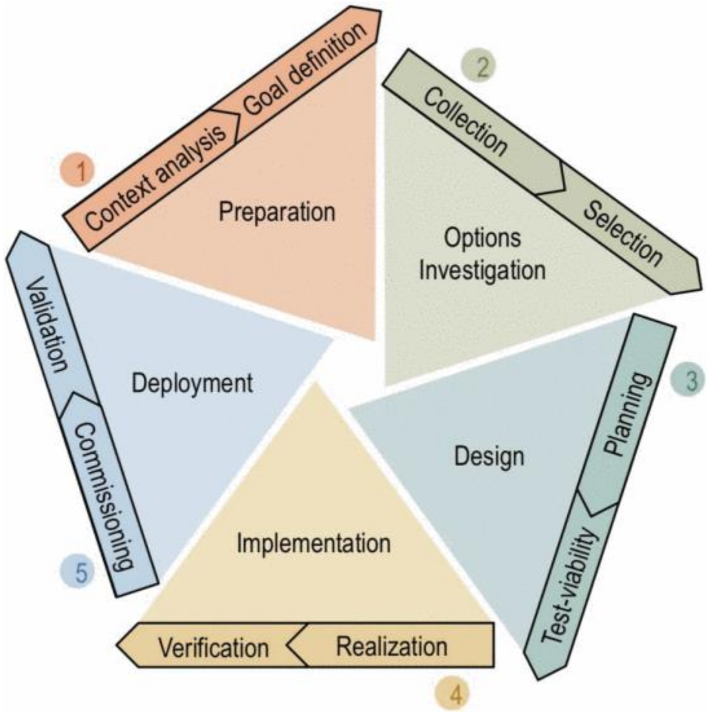

Figure 2.7 The migration process for CPPSs (Calà et al., 2017)

Orellana & Torres, (2019) proposed a transition process to transform a legacy-based factory into a smart factory with vertical integration, which consisted of eight steps, as shown in Figure 2.8. The first step is the selection of indicators that will be used for evaluating the process. The second step is to define the inputs of the process in order to choose properly the sensors and signals that will be digitized. The third step is the selection of the data sources for feeding the indicators. The fourth step is modernizing legacy machines. The fifth step is the creation of dedicated networks in order to avoid data conflicts and to facilitate communication and data exchange with other systems and machines. The sixth step is the generation of processes alarms in case of faults and changes in the process. The next step is the feedback and process monitoring. The final step is the installation of sensors and meters.

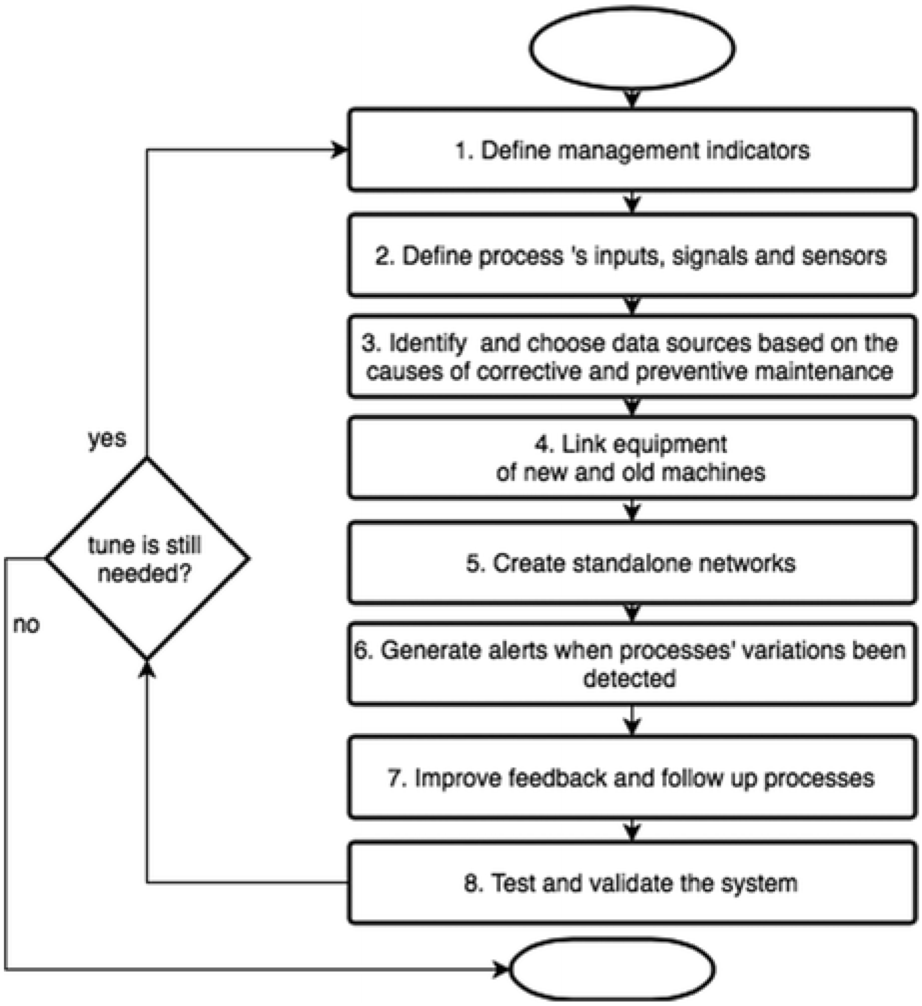

Figure 2.8 Transition process (Orellana & Torres, 2019)

Concluding, these transformation processes shaped the path towards CPPSs iteratively and stepwise with a defined sequence of activities. However, no models, tools or technologies were developed to support manufacturers to perform these steps.

2.3.3 Conclusion

Based on the literature analysis performed in Section 2.3.1 and Section 2.3.2, a research map of transformation methods is proposed, as shown in Figure 2.9. Many existing studies are concept proposals and transformation techniques are still in the early phase of maturity, only validated by experiments and usually one specific case study scenario. The research focus in the industry practices until now has been collecting data from various systems for creating additional value-added services rather than transforming, evolving, migrating, or retrofitting the existing legacy systems into CPPSs. Thus, further exploration and enhancement of these techniques and methodologies are still needed to ensure their applicability in real-world cases. For example, a platform that can offer the technological resources and functional components required in CPPSs could be developed to automate and standardize the process to transform legacy systems into CPPSs.

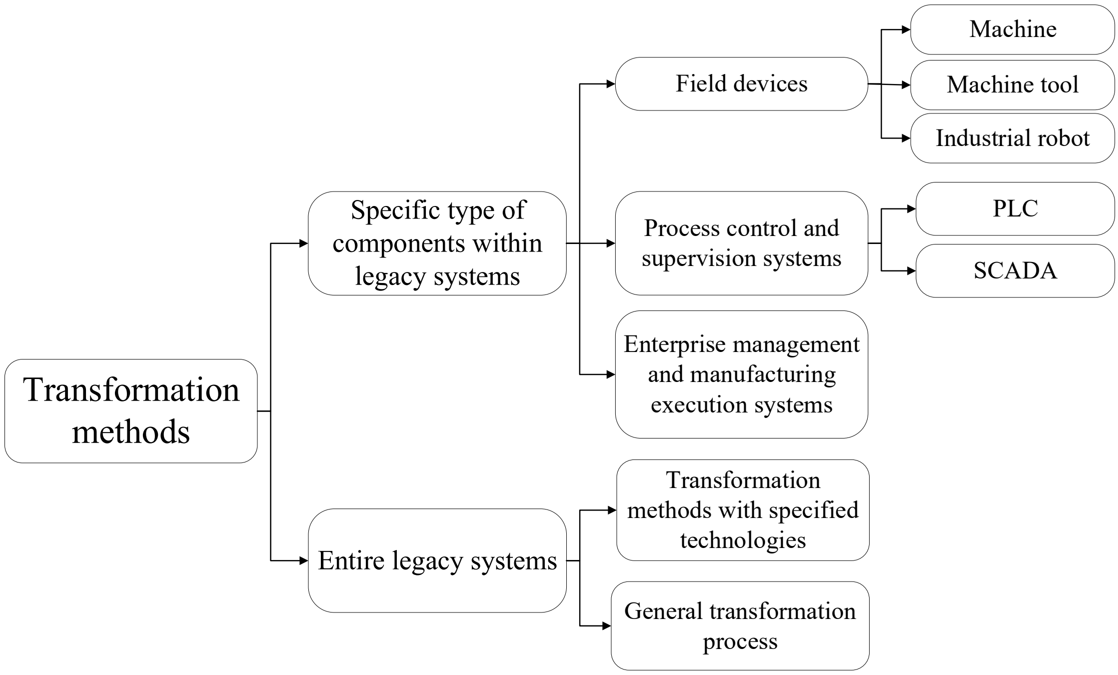

Figure 2.9 A research map of transformation methods of legacy systems into CPPSs

2.4 Research gaps and their connections with research questions

In order to answer the research questions posed in Section 1.3, some lessons and inspiration can be drawn from the above-mentioned literature reviews, and research gaps can also be identified so that our contributions can be positioned accordingly. In the reminder of this subsection, research gaps and their connections with research questions are presented.

- RQ1: What is the current research status of CPPSs and the transformation of legacy systems into CPPSs?

This question has been answered in Section 2.2.3 and Section 2.3.3. It is not repeated again.

- RQ2: Which elements need to be considered for the transformation towards CPPSs?

For answering this question, we extract some useful articles from the literature we reviewed previously, as shown in Table 2.3. The elements that need to be considered for the transformation consist of two parts: existing elements to be transformed and new elements to be installed.

Table 2.3 Summary of studies on transformation methods of specific types of components

Reference	**Existing elements to be transformed**	**New elements to be installed**
(Gunka et al., 2013)	Enterprise application	Cloud
(R. G. Lins et al., 2017)	CNC machine	IoT sensor
(Arjoni et al., 2017)	Robotic Arm, CNC Machine	Embedded Systems, IoT Sensor
(Godoy & González Pérez, 2018)	Communication network within the Flexible Manufacturing System (FMS)	Ethernet connectivity
(Mourtzis et al., 2018)	Machine tool	OPC-UA
(Botcha et al., 2018)	Machine tool	Sensor wrapper
(Lima et al., 2019)	CNC machine	Energy measurement industrial sensor, IoT gateway
(Lucke et al., 2019)	Machine	Sensor
(Bjetak et al., 2019)	PLC	IoT sensor
(Ooi et al., 2020)	Manufacturing machine	Wireless vibration sensor
(Etz et al., 2020)	Industrial robot	OPC UA
(T. Lins & Oliveira, 2020)	Robotic Arm	IoT Device, Embedded System, DB, Cloud, Web
(Khan et al., 2020)	SCADA	Cloud
(Pessoa et al., 2018)	Legacy production system	OPC UA, MQTT, Cloud
(Lass & Gronau, 2020)	Legacy production system	Communication middleware

As can be seen from Table 2.3, the elements that need to be considered for the transformation mentioned in existing studies include CNC machine, robotic arm, machine tool, PLC, SCADA, enterprise application, sensor, embedded system, Ethernet, OPC UA, MQTT, communication middleware, IoT gateway, cloud and web. However, these mentioned elements in literature are not complete. According to the definition of CPPSs, these elements are mainly those covered by technological agents and IT agents of CPPSs. Elements not mentioned in literature are those covered by human agents and those resulting from the synergy between these agents, such as business processes. To guarantee that the transformation will keep up with all new changes brought by CPPSs, it is necessary to define all the elements that need to be considered for the transformation towards CPPSs. To this regard, we propose to use a modeling approach to contain all elements of CPPSs. Modeling approaches require common terminology for defining and classifying CPPS elements. The elements mentioned in the existing studies in Table 2.3 have a low level of abstraction, which makes them difficult to be adapted to different use cases. For example, the element "MQTT" is suitable for transforming legacy system A into a CPPS, while the element "Ethernet" is suitable for transforming legacy system B into a CPPS. But if the abstraction level of these elements is raised and their common category is found, i.e., the element "communication protocol", instead of MQTT and Ethernet, it can be used both for legacy systems A and B. Therefore, a meta-model with a high level of abstraction and sufficient completeness should be proposed, which could have a lot of freedom in implementation and be applied to different use cases of CPPSs. Based on this research gap, Chapter 3 presents a meta-model of CPPSs, which defines all the essential elements of CPPSs.

- RQ3: How to identify the elements that need to be added and modified in legacy systems for being CPPSs and what is the transformation sequence of these elements?

In existing studies, stepwise methods are proposed to identify the elements that need to be added and modified in legacy systems for being CPPSs. These methods present some similarities. In summary, in the initial stage, they all considered three steps: i) the legacy system is analyzed ii) the target system is defined, iii) the gap analysis between the legacy system and the target system is made. Therefore, we could reference these three steps. However, in the gap analysis, existing studies rarely give the transformation sequence of the elements that need to be added and modified. Although a few studies have given the transformation sequence, the elements they consider are not complete, for example in (T. Lins & Oliveira, 2020). To this regard, our proposed meta-model of CPPSs that presents the complete elements can be used as the reference. Through instantiating the meta-model, the transformation sequence of these elements can be obtained. This will be presented in Chapter 4.

- RQ4: How to evaluate the benefits of the transformation solution?

Most of the existing studies on the topic of transformation stop at presenting their concepts and only a few of them have performance indicators to evaluate the potential benefits after following their transformation solutions. However, the evaluation of the transformation solution before its real implementation can avoid risks, so it is very important. To answer this question, we extracted the articles that include the evaluation of the transformation solution from the previously reviewed articles, as shown in Table 2.4.

Table 2.4 Summary of transformation methods with evaluated performance indicators

Reference	Key Performance Indicators (KPIs)	Type of analysis
(Arjoni et al., 2017)	Stability, communication capability	Qualitative analysis
(Orellana & Torres, 2019)	Gros profit (reliability, energy consumption, material losses, quality costs, non-productive times, corrective maintenance)	Quantitative analysis
(T. Lins & Oliveira, 2020)	Real-time communication capability (delivery time) Energy efficiency (energy consumption)	Quantitative analysis
(Khan et al., 2020)	Real-time communication capability (communication latency time)	Quantitative analysis
(Lass & Gronau, 2020)	Flexibility (time efforts required for reconfiguration)	Quantitative analysis
(Di Carlo et al., 2021)	Security, Maintainability, Plant control, Access to data	Qualitative analysis

From Table 2.4, it can be found that there are two main types of analysis for evaluating the transformation solution: i) Qualitative analysis describes the qualities or characteristics and is expressed in words or phrases using natural language. For example, Di Carlo et al., (2021) evaluated the KPI “access to data” using the linguistic terms “yes” and “no”. The strength of the qualitative analysis is that it can produce in-depth and illustrative information to understand various dimensions of the problem. But the evaluation metrics cannot be analyzed statistically and are open to bias. In addition, linguistic characterizations are less specific and precise than numerical ones (Oleghe & Salonitis, 2015), ii) Quantitative analysis provides data that can be expressed in numbers and the basic form is mathematical modeling. It requires the standardization of data collection to allow statistical comparison. The great advantage is its objectivity. But quantitative data is not always easy to collect. In addition, not all aspects can be measured with quantitative metrics so this limits the scope of the evaluation (Oleghe & Salonitis, 2015). It can be found that existing research either focuses on quantitative analysis or qualitative analysis, but no one has suggested a complementary use of the two kinds of analysis. Because quantitative and qualitative analysis has their own advantages and disadvantages and plays different roles in research, we propose to use both of them.

For the quantitative analysis, if the meaning and the way for calculating KPIs are not provided, its value can be the source of conflict. For example, T. Lins & Oliveira, (2020) and Khan et al., (2020) both want to evaluate the real-time communication capability. T. Lins &

Oliveira, (2020) used the delivery time, while Khan et al., (2020) used communication latency time. This makes it impossible to compare and select the best solution among different research proposals. Thus, the employment of standardized KPIs is proposed in our thesis. The ISO 22400 standard (ISO 22400–1, 2014; ISO 22400–2, 2014) compiles a list of 34 KPIs that used in the manufacturing industry. Therefore, we propose to make the quantitative analysis based on the ISO 22400 standard.

For the qualitative analysis, existing studies only considered the technical dimension. However, other dimensions, e.g., the organizational dimension, are affected by new technologies brought by CPPSs. Therefore, we propose to consider how the transformation affects the overall legacy systems under three dimensions (technological, informational and organizational dimensions) simultaneously.

Chapter 4 introduces the evaluation of transformation solutions through quantitative and qualitative analysis.

Chapter 3: Meta-model of CPPSs

This chapter is based on the following publications (X. Wu et al., 2021) and (X. Wu et al., 2019a):

- Wu, X., Goepp, V., Siadat, A., & Vernadat, F. (2021). A method for supporting the transformation of an existing production system with its integrated Enterprise Information Systems (EISs) into a Cyber Physical Production System (CPPS). *Computers in Industry*, 131, 103483.
- Wu, X., Goepp, V., & Siadat, A. (2019). The integrative link between cyber physical production systems and enterprise information systems. *The 49th International Conference on Computers & Industrial Engineering (CIE 49)*, Beijing, China.

Abstract

The goal of this chapter is to answer research question #2 "which elements need to be considered for the transformation towards CPPSs?". Therefore, a meta-model of CPPSs which defines all the essential elements and their relations is proposed. Firstly, the way for building the meta-model is explained, which is based on the 5C architecture and enterprise modeling standards, in the form of a UML class diagram. Then, the object classes extracted from the 5C architecture are explained and their replacement terms in literature are listed. Next, the reason for selecting the object classes related to EISs from the enterprise modeling standards is also explained. Finally, the relationships between these object classes are illustrated.

3.1 Introduction

When transforming legacy systems into CPPSs, which elements need to be considered should be identified first. However, due to the complexity and structural opacity of CPPSs, existing literature offers no consensus regarding the essential elements in CPPSs, which makes it an obstacle to the transformation of legacy systems to CPPSs.

A model is an abstract representation of a real system which may be a representation of the structure of the system, the activity flow of the system or the possible states of the system. In order to represent the essential elements in CPPSs, a CPPSs model that is made up of elements, such as CNC machines and robots, can be built. However, the CPPSs model is applicable solely to a specific kind of production system. In this case, a CPPSs meta-model with a higher level of abstraction compared to the CPPSs model should be proposed because it allows the user to capture and re-use elements common to different kinds of production systems, and thereby extends its applicability. The CPPSs meta-model is a re-usable reference model which defines the class set (domain concepts) and rules (structural and semantic constraints) for building CPPSs models (Cramer et al., 2021; Lechevalier et al., 2018). The relation between system, model and meta-model is shown in Figure 3.1. Once the meta-model is built, it can be used as a generalized framework to study the elements that need to be transformed for being CPPSs in different brownfield scenarios. Therefore, the objective of this chapter is to build a CPPSs meta-model that defines all the essential elements of CPPSs. In addition, the relations among these elements are also clarified because the emergence of CPPS is inherently the result of relations among these elements.

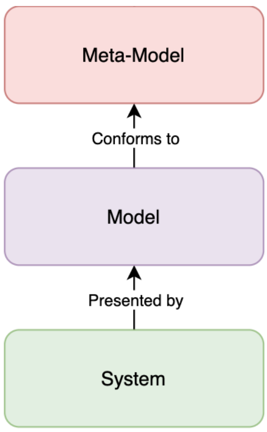

Figure 3.1 Relation of system, model, and meta-model (Sami, 2020)

The rest of this chapter is organized as follows: Firstly, Section 3.2 presents the way for building the meta-model. Then, in Section 3.3, the object classes of the meta-model are introduced, which consists of two parts, extracted from the 5C architecture and extracted from the enterprise modeling standards. Finally, the relationships between these object classes are illustrated in Section 3.4.

3.2 The way for building the meta-model

To build the meta-model of CPPSs, we use the UML class diagram, which is also appropriate for modeling systems in a non-technical manner, in addition to its use in structuring code. Following the notation of UML class diagrams, all elements in CPPSs should be illustrated using object classes. An object class is a container for a number of objects that share specific characteristics, semantics, and behaviors (OMG, 2011).

Among the modeling architectures of CPPSs that we reviewed in Chapter 2, the 5C architecture is the most popular and broadly accepted one and incorporates most of the elements of CPPSs. Therefore, we use it as a reference to specify object classes in the meta-model. Although the 5C architecture covers most of CPPS elements, it lacks the classes related to EISs. Specifically, EISs include three main dimensions, namely informational, technological and organizational dimensions (Reix et al., 2016), but the 5C architecture only incorporates the classes related to the informational and technological dimensions of EISs, such as integrated software packages like ERP systems, and no classes related to the organizational dimension of EISs. We propose to build the missing classes related to EISs on the basis of the enterprise modeling standards (ISO 19439, 2006; ISO 19440, 2020) because they precisely define a set of enterprise modeling constructs that could be selected as the object classes for representing EISs. Therefore, object classes of the meta-model are extracted from two parts: the 5C architecture and enterprise modeling standards. For the proposed meta-model of CPPSs, we do not include attributes and operations (i.e., methods) of the classes because the meta-model should be as generic as possible.

After identifying all object classes in the meta-model, the relationships between these classes are established and can be divided into three categories: i) relationships between the classes extracted from the 5C architecture, ii) relationships between the classes extracted from the enterprise modeling standards, and iii) relationships between the classes extracted from the 5C architecture and those extracted from the enterprise modeling standards. The third category of relationships is further described by three kinds, namely, informational, technological and organizational relationships, linked to the three dimensions of EISs. To detail the relationships between object classes, UML provides six relationships, namely, association, inheritance, realization, dependency, aggregation and composition. For the proposed meta-model of CPPSs, relationships between object classes are plotted by “association” which indicates possibilities for information exchange, "aggregation" and "composition" which indicate possibilities for the integration of CPPSs elements, and "dependency" which indicated the needs or dependencies of one element, the client, to another element, the supplier.

To have a general overview of the meta-model, it is presented here, as shown in Figure 3.2, where the rectangles represent object classes and the lines represent relationships between the classes. The detailed description of the meta-model, including its object classes and the relationships between these object classes, are presented in the following sections.

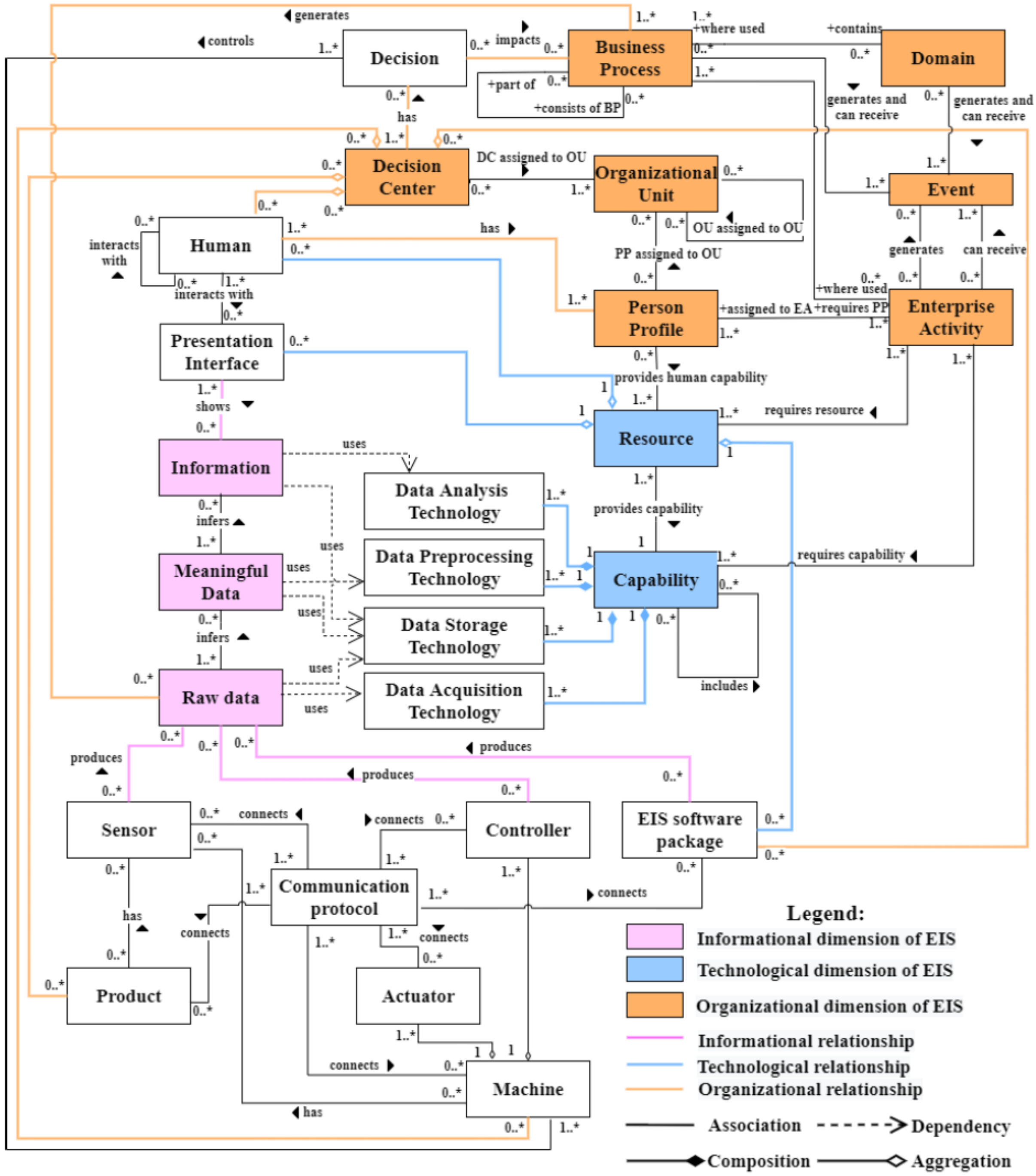

Figure 3.2 Meta-model of CPPSs

3.3 Object classes in CPPSs

3.3.1 Object classes extracted from the 5C architecture

Based on the description of each level of the 5C architecture obtained from (J. Lee et al., 2015), a set of key-nouns (in bold) have been extracted to become object classes of CPPSs. For example, part of the description at the connection level is "acquiring **data** from **machines** and their components is the first step and the data might be directly measured by **sensors** or obtained from **controllers** or **EIS software**" (J. Lee et al., 2015). From this sentence, the following classes are identified: *data*, *machine*, *sensor*, *controller* and *EIS software*. The process for extracting the object classes at other levels is the same, therefore we do not detail them anymore. One thing worth mentioning is that there are no new classes at the C5 level because it only applies the decisions made at the C4 level to the C1 level. However, smart product, which is an important element in the definition of CPPSs, is not emphasized in the 5C architecture. Therefore, a new object class "Product" is added at the connection level. The results of all the extracted object classes for the five levels are shown in Table 3.1.

Table 3.1 Object Classes extracted from the 5C architecture

Levels	Object Classes extracted from the 5C architecture
C1	Product, Machine, Sensor, Actuator, Controller, Communication Protocol, EIS Software Package, Raw Data, Data Acquisition Technology, Data Storage Technology
C2	Data Preprocessing Technology, Meaningful Data
C3	Data Analysis Technology, Information
C4	Presentation Interface, Human, Decision
C5	(nil)

In CPPSs literature, some different terms may be used to express the same meaning as our defined object classes. Therefore, to reach a consensus on the meaning of these classes and to make our meta-model generic, meanings of these object classes are explained and their replacement terms in the literature are presented as follows:

- "Product" is defined as a key subject of industrial value creation, which includes raw materials and (semi-)finished products. Raw materials are unprocessed substances, while semi-finished products are partially processed raw materials which have not yet been assembled to form a finished product. In CPPSs literature, similar terms used in place of “Product” are “raw material” (Pantano et al., 2020), “finished goods” (Pantano et al., 2020) and “workpiece” (C. Liu & Jiang, 2016).

- “Machine” is defined as “a piece of equipment with several moving parts that uses power to do a particular type of work” (Cambridge Dictionary, 2013). In CPPSs, it is used to refer to production machines (e.g., machines to manufacture or assemble raw material and products), auxiliary machines (e.g., logistic systems to transport raw material and products), and storage systems. In CPPSs literature, similar terms used in place of “Machine” are “machinery” (Thiede et al., 2016), “physical equipment” (Darwish & Hassanien, 2018), “robot” (Ma et al., 2017), “conveyor” (L. Wang et al., 2015), “transportation means” (Gronau & Theuer, 2016), “machine tool”, and “Automated Guided Vehicles (AGV)” (Darwish & Hassanien, 2018).
- “Sensor” is defined as an element that observes system states and changes in the physical environment and transforms the gathered data into electronic signals (C. Berger et al., 2016). Sensors can observe one or multiple measurands, such as temperature, motion, and light. In CPPSs literature, other terms for “Sensor” are “metrology equipment” (L. Wang et al., 2015), and “measurement systems” (Meisen et al., 2016).
- “Actuator” is defined as an element that translates received electronic signals from the cyber world into mechanical movements within the physical world. Actuators can be differentiated according to the seven main types of mechanical movements induced: spring, valve, electricity, magnetism, hydraulics, pneumatics, and thermal energy (Nof, 2009). In CPPSs literature, another term for “Actuator” is “actor” (Strang & Anderl, 2014).
- “Controller” is defined as a device that controls production processes in order to achieve human or system objectives. In CPPSs literature, other terms used to refer to “Controller” are “control component” (Zhu et al., 2011), “embedded controller” (Gawand et al., 2015), “microcontroller” (Mourtzis & Vlachou, 2018) and “PLC” (Bjetak et al., 2019).
- “Communication Protocol” is defined as the entirety of communication hardware and software consisting of two parts:

  i) Object-to-object interaction within a CPPS. This does not include interactions between humans and the inner system, which are covered by the object class “Presentation Interface”. Due to the fact that CPPSs may span multiple production sites, the communication protocols can connect geographically distributed elements.

If elements are geographically close to each other, local wired or wireless networks can be used; otherwise, the Internet or peer-to-peer networks must be used, both of which are capable of sharing large amounts of information among locally distributed systems (Hawa et al., 2017). Therefore, the communication protocol for object-to-object interaction within a CPPS includes physical cables, wireless communication, Bluetooth, network adapters, network routers, and network communication protocols.

ii) Intersystem communication by the Ethernet and IP networks (Schlechtendahl et al., 2015). As CPPSs are "systems of systems", a special characteristic of CPPSs is their ability to connect with multiple other external systems beyond their system boundaries, such as other CPPSs and ERP (S. Berger et al., 2021).

In CPPSs literature, other terms used to refer to "Communication Protocol" are "network" (B. Vogel-Heuser et al., 2014) and "CPS network infrastructure" (Yang et al., 2017), "gateway" (Schlechtendahl et al., 2015), "cross-layer infrastructure" (Foehr et al., 2017), and "connection to other systems" (Monostori, 2014).

- "EIS Software Package" is defined as operating software for production machines and human beings. It mainly refers to six types of software packages: ERP, MES, CRM, Supply Chain Management (SCM), Product Lifecycle Management (PLM) and Business Intelligence (BI) (Romero & Vernadat, 2016). It is worth noting that security and privacy issues are major challenges for CPPSs (Ma et al., 2017). We regard CPPSs protection to be part of "EIS software package" (e.g., user authentication systems, or intrusion detection systems), and therefore it is not explicitly mentioned as a respective object class within the meta-model. In CPPSs literature, similar terms for "EIS Software Package" include "enterprise systems" (J. Lee et al., 2020), "enterprise information systems" (Drăgoicea et al., 2019) and "enterprise software systems" (Frischbier et al., 2014).
- "Raw Data" is data that has not been processed for use. In production systems, raw data comes from a variety of sources and can be classified into three categories (J. Lee et al., 2020):

  i) Sensor data that is collected from built-in sensors or directly via the machine-controller as well, such as vibration, pressure and temperature.

  ii) Shop floor data that are related to production count, quality count, inventory level monitoring, factory logistics, operating conditions, expert estimates, etc. For example, RFID can identify, track and manage data related to materials, inventory, production and scheduling orders in the shop floor.

iii) Enterprise/management data that are obtained from EIS software packages like ERP, SCM, and PLM.

- “Data Acquisition Technology” refers to software and hardware that we use to acquire the raw data during production processes. In CPPSs literature, a similar term for “Data Acquisition Technology” includes “data collection techniques” (H. Tao et al., 2020).
- “Data Storage Technology” refers to software and hardware that we use to store data and information during production processes. With regard to data storage, the volume, the velocity of incoming data, the rate at which the data are accessed, as well as types of data to be stored are important aspects to be considered.
- “Data Preprocessing Technology” refers to preprocessing operations on collected raw data for getting meaningful data. Data preprocessing involves three primary tasks (J. Lee et al., 2020):

  i) Data suitability assessment that includes data quality checks, data cleaning operations, segmentation, and resampling operations.

  ii) Data background identification/working regime identification. Working regime identification is an important step because a machine might perform totally different from one working regime to another, and the developed analytical method can only work under specific ones. Clustering approaches, such as K-Means, Gaussian Mixture Model (GMM), and Visual Assessment of Cluster Tendency (VAT), are applied to identify various working regimes for gearbox, robotic arms, the spindle of machine tool, and other machines.

  iii) Feature extraction for getting reduced dimensional yet more significant features. Feature extraction methods include signal processing in the frequency and the time-frequency domain, like the Fast Fourier transform (FFT) for processing the high-frequency data from rotating machinery and wavelet transforms for bearing data analysis.
- “Meaningful Data” refers to the data obtained after data preprocessing operations of the raw data. Meaningful data is ordered, simplified, and meaningful features. In CPPSs literature, another term for “Meaningful Data” is “information” (Bagheri et al., 2015).
- “Data Analysis Technology” refers to a deeper and advanced analysis of meaningful data for getting useful information. Data analysis technology uncovers hidden patterns, unknown correlations, and other useful information from manufacturing systems and integrates the obtained information with other technologies to improve

productivity and innovation. Recently, AI-powered analytics methods enable us to comprehend data to identify anomaly patterns before they could occur, learn from previous experience and predict demand patterns on the shop floor. In CPPSs literature, similar terms for “Data Analysis Technology” include “data processing” (Luo et al., 2019) and “data analytics” (ur Rehman et al., 2019).

- “Information” refers to the useful information obtained after data analysis operations of the meaningful data. In CPPSs literature, another term for “Information” is “knowledge” (Bagheri et al., 2015).
- “Presentation interface” is used as an umbrella class that enables the human-system interaction. It includes two parts: i) cognitive assistance software that supports information and knowledge management. The cognitive assistance software is able to document and analyze information and then recommend appropriate actions to humans in an accessible manner. In CPPS literature, other terms for the cognitive assistance software are “human assistance” (L. Wang et al., 2015) and “decision support system” (Kunath & Winkler, 2018), and ii) communication devices that translate human input information into electronic signals or system output information and vice versa. The human input information may be provided by humans’ touch, gestures, or voice, while system output information may be provided by, for example, visualization and acoustics. Examples of communication devices are touch-screens, keyboards and buttons for input information, and computer screen, speakers, and signal lights for output information. Other term for communication devices in CPPSs literature is "communication tools" (Kassner & Mitschang, 2015). Finally, in CPPSs literature, similar terms for “Presentation interface” include “human machine interface” (Monostori et al., 2016), “user interface” (Darwish & Hassanien, 2018) and “human-system interface” (S. Berger et al., 2021).
- “Human” is defined as an essential element in CPPSs and has different roles depending on the maturity of CPPSs. There are four main scenarios of the interaction between humans and CPPSs: full, automation, tool and manual scenarios (Cardin, 2019; Dworschak & Zaiser, 2014). In a full scenario, humans only have a role of supervision of CPPSs, while CPPSs can take all the necessary decisions without any intervention of humans. In an automation scenario, most decisions are made by CPPSs, while human beings are guided by CPPSs to perform activities. Conversely, in a tool scenario, most decisions are made by humans, while CPPSs are guided by humans. In a manual scenario, all decisions are made by humans, while CPPSs only

provide data to humans. By clustering human roles in CPPSs, different kinds of humans can be identified, for example, operator (Zolotová et al., 2018), worker (Gräßler et al., 2021), manager (Fantini et al., 2018), supervisor (Müller et al., 2017), and decision-maker (Müller et al., 2017). In CPPSs literature, similar terms for "Human" are "human beings" (S. Berger et al., 2021) and "human users" (Cimini et al., 2020).

- "Decision" refers to a series of actions to be taken in production systems based on the outcomes of the data analysis. Once the data analysis is performed, actionable and insightful information can be obtained. Such information can be utilized by automated decision-making units or humans to make decisions, such as maintenance recommendations and optimal scheduling strategies.

3.3.2 Object classes extracted from enterprise modeling standards

The enterprise modeling standard ISO 19439 provides four enterprise model views to describe the various aspects of the enterprise, including the information view, the resource view, the function view and the organization view. The four enterprise model views can be partially mapped to the three dimensions of EISs described in Section 1.2 as follows and are presented in Table 3.2.

- Information view, which represents the information used in an enterprise, can be partially mapped to the informational dimension of EISs.
- Resource view, which represents the enterprise assets (e.g., technological components) that are needed for carrying out the enterprise operations, can be partially mapped to the technological dimension of EISs.
- Function view, which represents the business processes in an enterprise, can be partially mapped to the organizational dimension of EISs.
- Organization view, which represents the organization, organizational relationships and the decision-making responsibilities in an enterprise, can be partially mapped to the organizational dimension of EISs.

The enterprise modeling standard ISO 19440 defines a set of enterprise modeling constructs conforming to the four enterprise model views in ISO 19439. Therefore, some of these enterprise modeling constructs can represent the three dimensions of EISs. These enterprise modeling constructs and the reasons for choosing which modeling constructs as the object classes to represent EISs are presented in Table 3.2.

Table 3.2 Selection of object classes for EISs from enterprise modeling constructs

EISs dimensions	**Enterprise model views**	**Enterprise modeling constructs**	**Object classes of EISs (×:exclude; ✓:include)**	**Reasons for including or excluding the enterprise modeling constructs**
Informational dimension	Information view	Enterprise Object	×	The object classes *Raw Data, Meaningful Data* and *Information* specified in the 5C architecture can better represent the informational dimension.
		Enterprise Object View	×	
		Order	×	
		Product	×	
Technological dimension	Resource view	Resource	✓	Represents software, hardware and human resources.
		Capability	✓	Represents data acquisition, storing and processing capabilities that are provided by a *Resource* to support the execution of tasks required by an *Enterprise Activity*.
		Functional Entity	×	Represents a specialization of the class *Resource* to execute functional operations, so it could be covered by the class *Resource.*
		Operational Role	×	Represents the human skills to perform operational tasks, so it could be covered by the class *Person Profile* which can represent all human skills.
Organizational dimension	Function view	Domain	✓	Represents the functional area of an EIS.
		Business Process	✓	Represents a partially ordered set of *Business Processes* that are executed to realize business objectives.
		Enterprise Activity	✓	Represents the lowest level of process functionality that is needed to realize a basic task within a business process.
		Event	✓	Represents the initiation of a state change in the enterprise, which shall trigger business processes or enterprise activities or both.
	Organization view	Person Profile	✓	Represents the human skills available to serve the organizational and operational tasks.
		Organizational Role	×	Represents the human skills to perform organizational tasks, so it could be covered by the class *Person Profile* which can represent all human skills.
		Organization Unit	✓	Represents the formal, hierarchical or administrative structure of an enterprise, or some combination thereof.
		Decision Center	✓	Represents the decisional structure of an enterprise.

3.4 Relationships between object classes

For the proposed meta-model, relationships of association, aggregation, composition and dependency are used. An association is a broad term that encompasses any logical connection or relationship between classes. The name of the association relationship is written in the middle of its line to give meanings to this relationship. In addition, they often have a small arrow to indicate the direction to read this relationship. The aggregation represents a “whole-part” relationship where a “whole” is composed of multiple “parts”. Thereby, a part can exist without the whole. The composition is very similar to the aggregation, with the only difference being its parts cannot exist without the whole. The dependency represents a special type of association, where one class is dependent upon another class. Thereby, the dependency exists between two classes if changes to the definition of one may cause changes to the other (but not the other way around). The multiplicity (cardinality) near the ends of relationships is an indication of how many objects may participate in the given relationship or the allowable number of instances of the element.

The relationships between object classes can be divided into three categories: i) relationships between the classes extracted from the 5C architecture, ii) relationships between the classes extracted from the enterprise modeling standards, and iii) relationships between the classes extracted from the 5C architecture and those extracted from the enterprise modeling standards. In Figure 3.2, the first two relationships are presented with black lines, and the last relationship is presented with colored lines, i.e., pink, blue and orange. Because the relationships between classes extracted from the enterprise modeling standard can be obtained directly from the ISO 19440, (2020), there is no need to repeat them. In this sub section, only the remaining two types of relationships are explained in detail as follows.

3.4.1 Relationships between the classes extracted from the 5C architecture

At the connection level, we assume that a *Machine* includes at least one *Actuator* and one *Controller*, otherwise, the machine would not be able to participate in the value creation process of CPPSs. The *Product* and *Machine* may have *Sensor* for data collection. The *Communication Protocol* may connect *Machine* and *Product* for remote control and data access. There are also associations between the *Sensor/Controller/Actuator* and the *Communication Protocol* because sensors, controller and actuators could be accessed directly via other elements (e.g., a central control panel) using the communication protocol. In addition, the *Communication Protocol* may connect with *EIS Software Package* for external data input. The

Raw Data might be directly measured by *Sensor* or obtained from *Controller* or *EIS Software Package* such as ERP and MES, which requires the use of *Data Acquisition Technology*. In addition, the Raw Data must be stored, which requires the use of *Data Storage Technology.*

At the data-to-information conversion level, *Meaningful Data* may be inferred from *Raw Data*, depending on *Data Preprocessing Technology*. In addition, *Meaningful Data* must be stored, for example, in a central server, which requires the use of *Data Storage Technology*.

At the cyber level, *Information* may be inferred from *Meaningful Data*, depending on *Data Analysis Technology*. In addition, *Information* must be stored, for example, in a cloud, which requires the use of *Data Storage Technology*.

At the cognition level, *Information* is presented in at least one *Presentation Interface*. Human-system interaction is achieved through the association between a Human and one or several *Presentation Interface* (e.g., touch screen or a Kanban with cognitive assistance software). In addition, human-human interaction, i.e., the collective work of two or more humans involving organizational aspects, social aspects, etc., is achieved through the self-association relationship of *Human*. *Decision* may be made by *Human*, *Product*, *Machine* or *EIS Software Package*.

At the configuration level, *Decision* controls the operations of *Machine*.

3.4.2 Relationships between the classes extracted from the 5C architecture and those extracted from enterprise modeling standards

According to the three dimensions of EISs, the relationships between the classes extracted from the 5C architecture and those extracted from the enterprise modeling standards can also be categorized into three kinds (respectively, informational, technological and organizational relationships) and are explained as follows.

- The technological relationships mean that EISs provide resources (such as hardware, software and human) and data-related capabilities (including data acquisition/storage/processing/analysis capabilities) to perform the processes of collecting, storing, processing and analyzing data in production systems. They define the technologies needed to support the production processes.
- The informational relationships mean that raw data could be acquired from sensors, controllers and EISs software packages and then information is represented in presentation interfaces. They lead to an understanding of the current information flow management.

- The organizational relationships mean that EISs support the business processes and decision-making processes in production systems through humans and other technological resources. They represent the combination of plant activities, decision-making and organizational alignment that can ensure and support business processes, leading to achieving dramatic enhancements in performance.

These three kinds of relationships at each level are presented in Table 3.3.

Table 3.3 Relationships between object classes extracted from the 5C architecture and object classes extracted from enterprise modeling standards

Level	Technological relationships	Informational relationships	Organizational relationships
C1	Capability & (Data Acquisition Technology, Data Storage Technology)	Raw Data & (Sensor, Controller, EIS software package)	(nil)
C2	Capability & Data Preprocessing Technology	(nil)	(nil)
C3	Capability & Data Analysis Technology	(nil)	(nil)
C4	Resource & (Presentation Interface, Human)	Information & Presentation Interface	Human & Person Profile, Decision Center & Decision, Decision Center & (Product, Machine, Human, EIS Software Package)
C5	(nil)	(nil)	Decision & Business Process, Business Process & Raw Data

3.5 Conclusion

A meta-model of CPPSs which defines all the essential elements and their relations is proposed, in the form of a UML class diagram. The object classes are extracted from the 5C architecture and enterprise modeling standards. The relationships between these object classes are plotted by “association”, “aggregation”, “composition” and “dependency” relationships that conform to the UML. Particularly, three kinds of relationships, namely, informational, technological and organizational relationships, are defined. To the best of our knowledge, it is the first meta-model of CPPSs proposed so far, which emphasizes the EISs dimension in CPPSs. Overall, the meta-model allows to represent a broad variety of different CPPSs when its object classes are instantiated.

Chapter 4: A method for transforming an existing production system with its integrated EISs into a CPPS

This chapter is based on the following publication (X. Wu et al., 2021):

- Wu, X., Goepp, V., Siadat, A., & Vernadat, F. (2021). A method for supporting the transformation of an existing production system with its integrated Enterprise Information Systems (EISs) into a Cyber Physical Production System (CPPS). *Computers in Industry*, 131, 103483.

Abstract

The goal of this chapter is to answer research question #3 "how to identify the elements that need to be added and modified in legacy systems for being CPPSs and what is the transformation sequence of these elements?" and research question #4 "how to evaluate the benefits of the transformation solution?". Firstly, the instantiation principles of the meta-model are described. Then, based on these instantiation principles, a method for the transformation of legacy systems into CPPSs is presented. As a result, a transformation matrix is proposed, which provides a high-level view of what should be improved (the elements that need to be added and modified) in the current production system and also suggests what steps can be considered to achieve the highest level of the 5C architecture. In addition, the evaluation of this transformation solution through quantitative and qualitative analysis is performed.

4.1 Introduction

Generally speaking, the transformation can be implemented by either adding new elements or modifying existing elements. Therefore, the first objective of this chapter is to identify which elements need to be added and modified and to indicate the transformation sequence of these elements by proposing a gap analysis step between the As-Is system and the To-Be system. Furthermore, after the transformation solution has been obtained, an evaluation should be performed in order to demonstrate the benefits of the transformation solution before further development of it. This evaluation can allow the manufacturer to decide whether to proceed with the development of the transformation solution or to start over. Therefore, the second objective of this chapter is to propose an evaluation of the transformation solution. Combining these two objectives, this chapter is dedicated to proposing a method that provides a structured process to guide manufacturers in transforming legacy systems into CPPSs.

The rest of this chapter is organized as follows. Firstly, Section 4.2 presents two principles for instantiating the meta-model. Then, in Section 4.3, based on these instantiation principles, a method for transforming legacy systems into CPPSs is presented, which identifies the elements that need to be added and modified and proposes the evaluation of the transformation solution through quantitative and qualitative analysis.

4.2 Instantiation principles of the meta-model

Instantiation principles of the meta-model are described as follows, which gives guidance for the instantiation process:

- Principle 1: Classes extracted from the 5C architecture should be instantiated layer by layer from the C1 level to the C5 level, because the 5C architecture gives a sequential workflow for the implementation of CPPSs. That is to say, if classes at the C1 level are not instantiated, it is impossible to instantiate classes at the C2 level and the same goes for other levels.
- Principle 2: At each level, the classes extracted from the 5C architecture should be instantiated first and then the classes extracted from the enterprise modeling standards that are associated with the technological, informational and organizational relationships at this level should be instantiated. In this way, the technological relationships are first considered, then the informational relationships and finally the organizational relationships. Indeed, if there are no technological relationships, it is impossible to obtain data/information and to have an informational relationship. Also,

if there are no informational relationships, it is impossible to support efficient business processes and decision-making and to have an organizational relationship.

Combining Principle 1 and Principle 2, the instantiation process starts with classes extracted from the 5C architecture of the C1 level and goes further to classes extracted from enterprise modeling standards that are associated with the technological, informational and organizational relationships at the C1 level. Then, this instantiation loop moves to the C2 level and repeats until the C5 level.

4.3 A method for the transformation towards CPPSs

In this section, based on the instantiation principles of the meta-model, a method for the transformation towards CPPSs is proposed as shown in Figure 4.1.

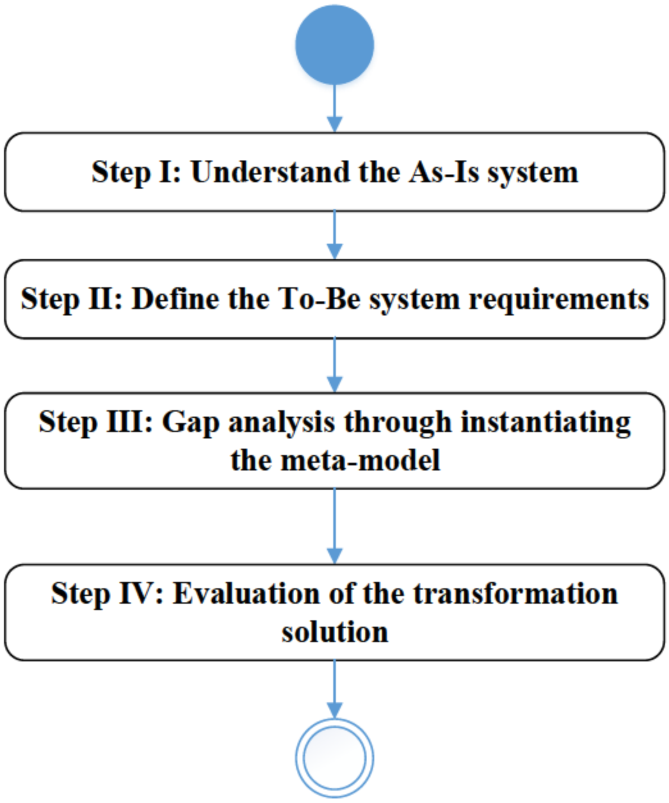

Figure 4.1 Method for transforming a production system with its integrated EISs into a CPPS

- **(1) Step I: Understand the As-Is system**

This step needs to understand the composition, functionalities, used technologies, architectures and production processes of the As-Is system. In addition, it also enables to assess the situation of the As-Is system in order to identify where improvements are needed.

- **(2) Step II: Define To-Be system requirements**

This step is a formal description of the To-Be system specification. System requirements can then be broken down into basic functions, and each of them can be fulfilled by dedicated object classes in the meta-model.

- **(3) Step III: Gap analysis through instantiating the meta-model**

According to the principles defined in Section 4.2, the gap analysis process performed by instantiating the meta-model is shown in Figure 4.2. It firstly maps the elements in the As-Is system to the object classes in the meta-model, then identifies the missing classes or those that need to be modified according to the To-Be system requirements, and finally instantiates these object classes. At each level, there are four kinds of mapping activities (mapping the classes extracted from the 5C architecture, mapping the classes extracted from the enterprise modeling standards that are associated with the technological, informational and organizational relationships) and one instantiation activity. The instantiation of the object classes is considered as the investigation of possible solution options according to the requirements and the choice of the optimal solution, without deeper technological details for their design and implementation. One thing worth mentioning is that it is not necessary to implement all five levels of the 5C architecture because CPPSs has different levels of maturity. To be specific, if all requirements can be met at a given level, the transformation process ends; otherwise, it goes to the next level until the C5 level. Therefore, at the end of each level, there is a checking activity to see whether it is required to go to the next level according to the To-Be system requirements.

To better understand the activities of the gap analysis process in Figure 4.2, an IDEF0 diagram (Figure 4.3) is proposed to analyze the data required by each activity, including inputs, outputs, resources (or mechanisms) that support the activity, and constraints (controls) required for the activity. There are five activities in Figure 4.3 that are consistent with the activities in Figure 4.2. After the gap analysis, a transformation matrix of the object classes is proposed to immediately visualize the gap between the As-Is and To-Be system, as shown in Table 4.1. This matrix is structured in rows and columns. The columns express the object classes in the meta-model, the instantiation of object classes in the As-Is system and the To-be system, and the three states of object classes (to be created, to be modified, and no modification) where each class should have one and only one state.

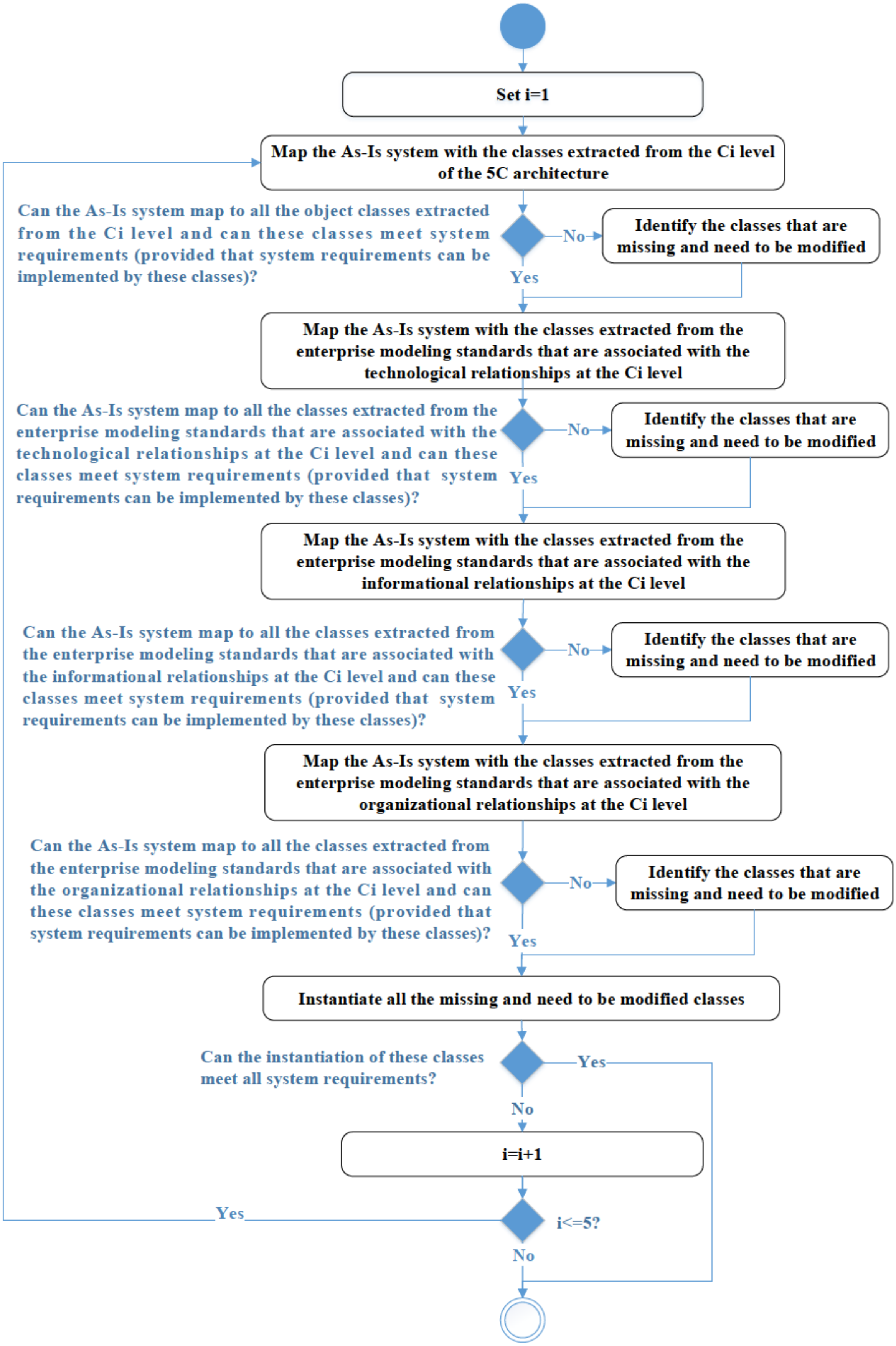

Figure 4.2 gap analysis process performed by instantiating the meta-model

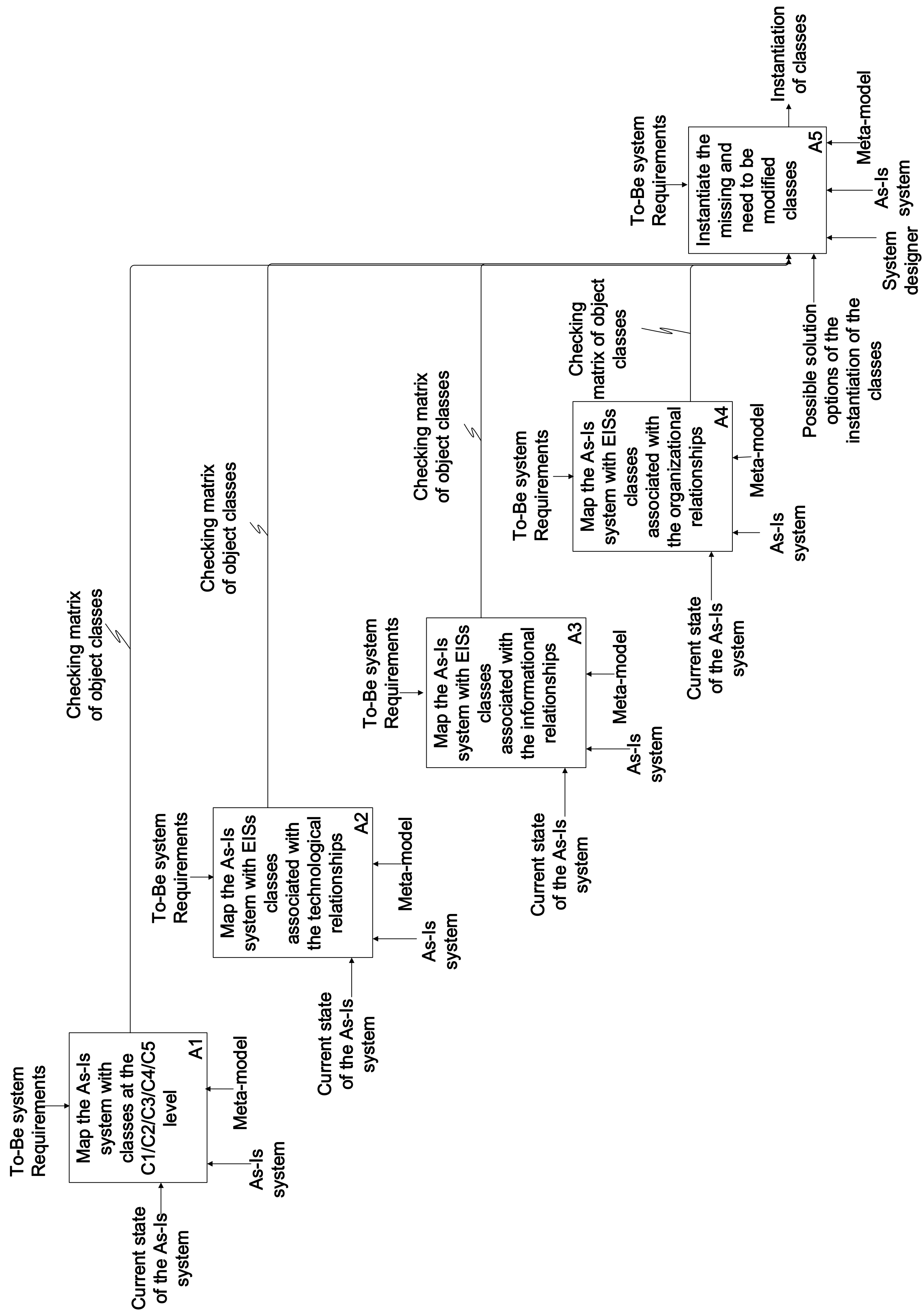

Figure 4.3 Activity A0 – Perform the gap analysis by instantiating the meta-model

Table 4.1 Transformation matrix of object classes

Object classes in the meta model		**Instantiation of object classes**		**State of object classes**		
		As-Is system	**To-Be system**	**To be created**	**To be modified**	**No modification**
C1	Product					
	Actuator					
	Sensor					
	Machine					
	Controller					
	EIS software package					
	Communication Protocol					
	Data Acquisition Technology					
	Data Storage Technology					
	Raw Data					
C2	Meaningful data					
	Data Preprocessing Technology					
C3	Information					
	Data Analysis Technologies					
C4	Presentation Interface					
	Human					
	Decision					
Informational dimension of EIS	Raw Data					
	Meaningful Data					
	Information					
Technological dimension of EIS	Resource					
	Capability					
Organizational dimension of EIS	Domain					
	Event					
	Business Process					
	Enterprise Activity					
	Person Profile					
	Decision Center					
	Organization Unit					

- **Step IV: Evaluation of the transformation solution**

After the transformation solution has been obtained in Step III, an evaluation should be performed in order to demonstrate the benefits of the transformation solution before further development of it. The evaluation supports the manufacturer to understand if the proposed transformation solution is feasible or unfeasible according to its positive or negative impact on the legacy system. In the end, the manufacturer can decide whether to develop this transformation solution by weighing the expected benefits against the actual obstacles.

To evaluate the benefits of the transformation solution, quantitative and qualitative analyses are used in a complementary way. The quantitative analysis is performed based on standard KPIs defined by the international standard ISO 22400. This standard defines 34 KPIs at the MOM level, but only 26 of them are considered in this thesis. Of these 8 KPIs not considered, 7 KPIs are not designed for discrete manufacturing (i.e., “inventory turns”, “finished goods ratio”, “integrated goods ratio”, “production loss ratio”, “storage and transportation loss ratio”, “other loss ratio”, and “equipment load ratio”), and one KPI is largely unexplored (i.e., “comprehensive energy consumption”). At the same time, the qualitative analysis is performed to evaluate the unmeasurable benefits of the transformation from three dimensions, i.e., technological, informational and organizational dimensions. The quantitative and qualitative analyses are presented as follows.

① **Quantitative analysis:**

We define three steps for conducting the quantitative analysis to evaluate the benefits of the transformation solution, as shown in Figure 4.4.

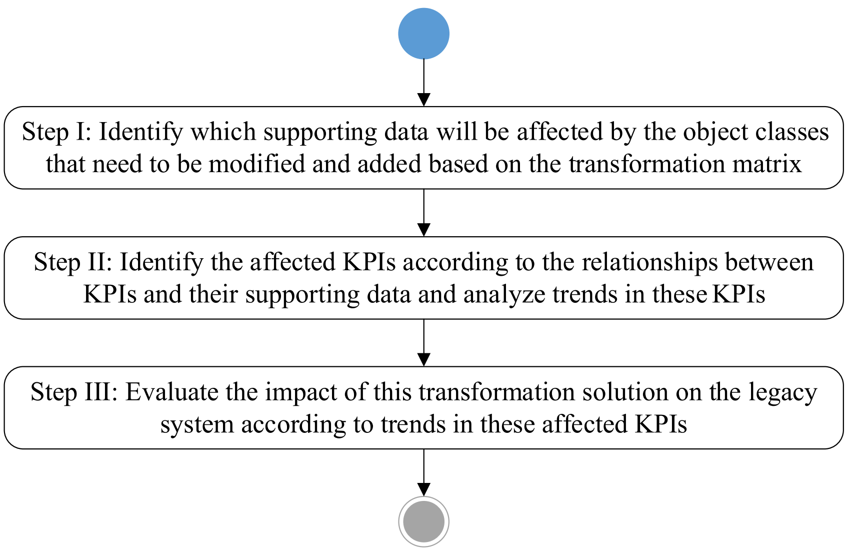

Figure 4.4 Quantitative analysis

- Step I: Identify which supporting data will be affected by the object classes that need to be modified and added based on the transformation matrix

After performing Step III, we obtain a transformation matrix showing object classes that need to be modified and added. The first step is to identify which supporting data are affected by these object classes. The supporting data are the data used for calculating KPIs. According to ISO 22400–2 (2014), the supporting data related to these 26 KPIs are listed in Table 4.2. They are categorized into time-related data, quantity-related data and quality-related data.

There is no fixed link between object classes and supporting data. This is because the same object class may affect different supporting data, depending on the purpose of modifying or adding this object classes. For example, if one of the results of the transformation matrix is to add a new sensor to detect the state of the machine in order to inform operators to solve the problem before it breaks down, we could identify that the affected supporting data is time-related data, e.g., ADET. But if the purpose to add this new senor is to detect non-conforming products and rework them, the affected supporting data will include quantity-related data, e.g., rework quantity. Therefore, the identification of affected supporting data can only be based on the purpose of modifying or adding object classes and the manufacturer's experience.

- Step II: Identify the affected KPIs according to the relationships between KPIs and their supporting data and analyze trends in these KPIs

ISO 22400–2 (2014) gives the formulas to calculate these 26 KPIs through their supporting data, as summarized in Table 4.3. From these calculation formulas, the relationships between KPIs and their supporting data can be obtained. In addition to the obvious relationships between the supporting data and KPIs shown in their calculation formula in Table 4.3, there are also implicit relationships between some other supporting data and these KPIs because these supporting data are interrelated. The relationships between these supporting data are summarized in Figure 4.5 and the meanings of these data are explained in Appendix A.

Table 4.2 Supporting data (summarized from (ISO 22400–2, 2014))

Category of data		Abbreviations of data	Full names of data
Time-related data	Actual times	ADET	Actual unit delay time
		ADOT	Actual unit downtime
		APAT	Actual personnel attendance time
		APWT	Actual personnel work time
		AUBT	Actual unit busy time
		AOET	Actual order execution time
		AUPT	Actual unit processing time
		AUST	Actual unit setup time
		APT	Actual production time
		AQT	Actual queuing time
		ATT	Actual transport time
	Planned times	PBT	Planned busy time
		PDOT	Planned operation time
		POT	Planned down time
		PRI	Planned runtime per item
	Maintenance times	TBF	Operating time between failure
		FE	Failure event
		TTF	Time to failure
		TTR	Time to repair
		CMT	Corrective maintenance time
		PMT	Planned maintenance time
Quantity-related data		GQ	Good quantity
		SQ	Scrap quantity
		RQ	rework quantity
		PQ	Produced quantity
		PSQ	Planned scrap quantity
Quality-related data		GP	Good parts
		IP	inspected parts
		USL	Upper specification limit
		LSL	Lower specification limit
		σ	Standard deviation
		X	Arithmetic average
		σ’	Estimated deviation
		X’	Average of average values

Table 4.3 Calculation formulas of KPIs (summarized from (ISO 22400–2, 2014))

Abbreviations of KPIs	Full names of KPIs	Formulas of KPIs
WE	Worker efficiency	WE=APWT/APAT
AR	Allocation ratio	AR=Σ AUBT/AOET
TR	Throughput rate	TR=PQ/AOET
AE	Allocation efficiency	AE=AUBT/PBT
UE	Utilization efficiency	UE= APT/AUBT
OEE	Overall equipment effectiveness	OEE=A*E*QR
NEE	Net equipment effectiveness	NEE= AUPT/PBT*E*QR
A	Availability	A=APT/PBT
E	Effectiveness	E=PRI*PQ/APT
QR	Quality ratio	QR=GQ/PQ
SeR	Setup ratio	SeR=AUST/AUPT
TE	Technical efficiency	TE=APT/(APT+ADET)
PR	Production process ratio	PR=ΣAPT/AOET
SQR	Actual to planned scrap ratio	SQR=SQ/PSQ
FPY	First pass yield	FPY=GP/IP
SR	Scrap ratio	SR=SQ/PQ
RR	Rework ratio	RR=RQ/PQ
FR	Fall off ratio	FR=(PQ-GQ)/PQ
Cm	Machine capability index	Cm=(USL-LSL)/(6* σ)
Cmk	Critical machine capability index	Cmku=(USL-X)/3 σ , Cmkl=(X-LSL)/3 σ , Cmk=Min(Cmku, Cmkl)
Cp	Process capability index	Cp=(USL-LSL)/(6* σ ’)
Cpk	Critical process capability index	Cpku=(USL-X’)/3 σ , Cpkl=(X’-LSL)/3 σ , Cpk=Min(Cpku, Cpkl)
MTBF	Mean operating time between failures	$\text{MTBF} = \frac{\sum_{i=1}^{FE} TBF_i}{FE + 1}$
MTTF	Mean time to failure	$\text{MTTF} = \frac{\sum_{i=1}^{FE} TTF_i}{FE + 1}$
MTTR	Mean time to repair	$\text{MTTR} = \frac{\sum_{i=1}^{FE} TTR_i}{FE + 1}$
CMR	Corrective maintenance ratio	CMR=CMT/(CMT+PMT)

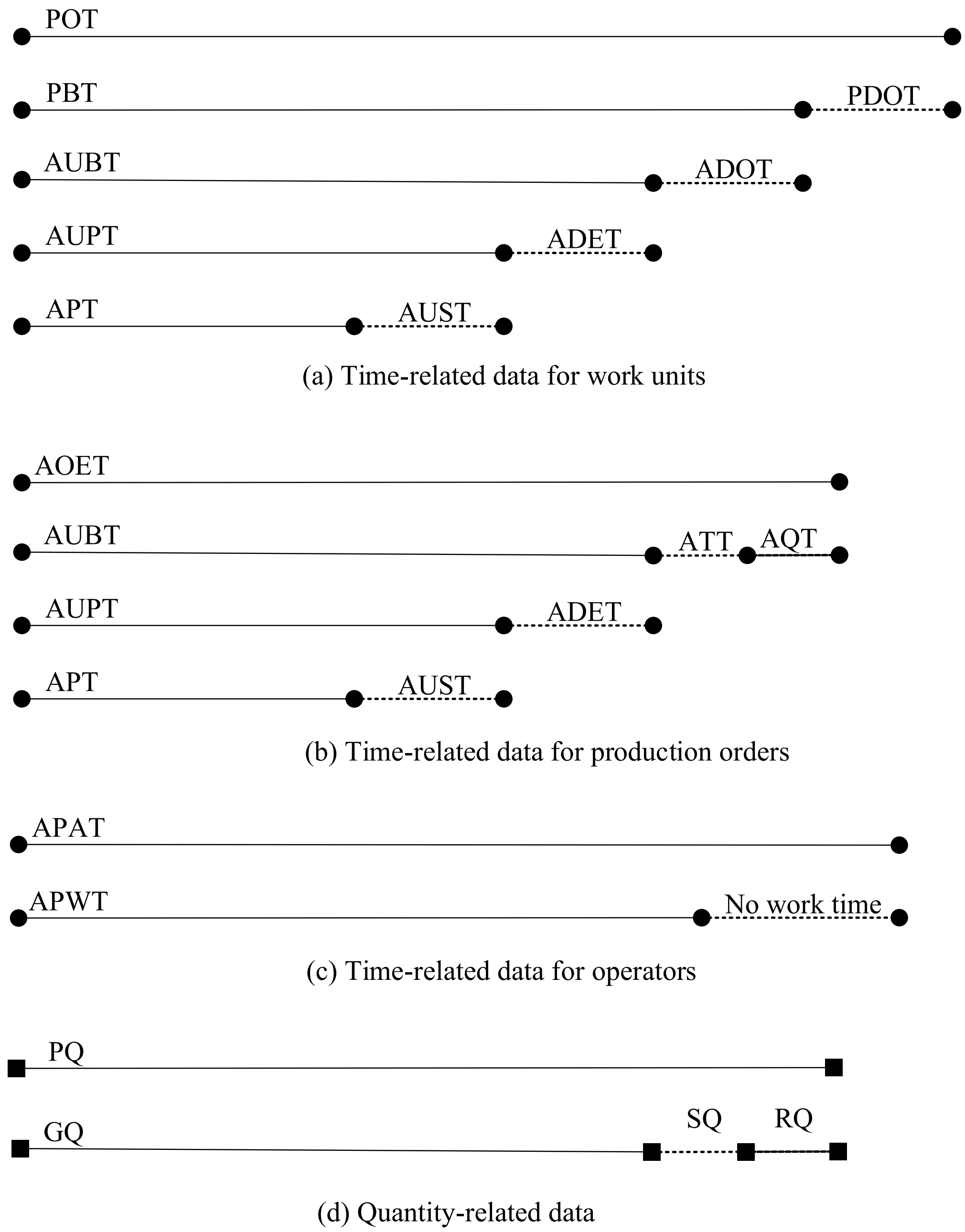

Figure 4.5 The supporting data with interactive relationships (summarized from (ISO 22400–2, 2014))

For the time-related data, it can be measured from the points of view of work units, production orders, or operators. Firstly, in terms of a work unit, the following time periods can be planned: *POT and PBT*. Such two time periods are not the same due to scheduled non-working time. Thus, to address the relationship between them, *PDOT* is introduced. The relationship between them is: POT=PBT+PDOT. However, the planned time may not be exactly performed in the production. Considering the actual down time, the following time periods are introduced: *AUBT* and *ADOT*. The relationship between them is:

PBT=AUBT+ADOT. Second, in terms of a production order, a work unit may need to load or unload the part, and the part may need to wait in a buffer or on a work unit due to its interactions with other working units. Such time periods are defined by *AOET*, *ATT* and *AQT*. The relationship between them is: AOET=AUBT+ATT+AQT. Considering the delay time and setup time for a work unit and also for a production order on the work unit, the following times are defined for both a work unit and a production order: *ADET*, *AUPT*, *AUST*, *APT*. Thus, the following relationships are obtained: AUBT=AUPT+ADET, AUPT=APT+AUST. Finally, in terms of an operator, the following time periods are defined: *APAT* and *APWT*. Such two time periods are not the same due to the time that the operator is not working.

For the quantity-related data, if all reworked parts are of good quality, then the relationship between these quantities can be described as: PQ=GQ+SQ+RQ.

Therefore, through these implied relationships, it is possible to derive the implicit relationships between these support data and KPIs. For example, according to Table 4.3, we can obtain that TR=PQ/AOET. As we have the following implied relationships, i.e., PQ=GQ+SQ+RQ, AOET=AUBT+ATT+AQT, AUBT=AUPT+ADET and AUPT=APT+AUST, we can obtain:

$$\begin{aligned}\mathrm{TR} &= \frac{\mathrm{GQ}+\mathrm{SQ}+\mathrm{RQ}}{\mathrm{AUBT}+\mathrm{ATT}+\mathrm{AQT}} = \frac{\mathrm{GQ}+\mathrm{SQ}+\mathrm{RQ}}{\mathrm{AUPT}+\mathrm{ADET}+\mathrm{ATT}+\mathrm{AQT}} \\ &= \frac{\mathrm{GQ}+\mathrm{SQ}+\mathrm{RQ}}{\mathrm{APT}+\mathrm{AUST}+\mathrm{ADET}+\mathrm{ATT}+\mathrm{AQT}}\end{aligned}$$

It can be concluded that TR is not only related to PQ and AOET, but also may be related to the following supporting data: GQ, SQ, RQ, AUBT, ATT, AQT, AUPT, ADET, APT, AUST.

In order to be clear about all relationships between these 26 KPIs and their supporting data, Table 4.4 and Table 4.5 are drawn. The rows are supporting data and the columns are KPIs. If a KPI may be positively (or negatively) correlated with a supporting data, the intersection of the corresponding row and column will be marked with a symbol + (or -). For direct relationships that are obtained from the calculation formulas of KPIs, symbols +* or -* are used, while for non-direct relationships, only + or - are marked. Kang et al., (2016) also proposed such tables, but they only considered 21 KPIs, and the relationships they presented were not complete. Compared to their work, the supplementary work we have done is marked in blue in Table 4.4 and Table 4.5.

After clearly understanding the relationships between KPIs and their supporting data, it is able to identify the affected KPIs according to Table 4.4 and Table 4.5 and also to analyze trends in these affected KPIs. For example, if in the previous step we identify that the affected supporting data is AUBT, we can find that when AUBT decreases (or increases), according to Table 4.4, it leads to an increase (or decrease) of TR, UE, and E and a decrease (or increase) of A, AR and AE.

Table 4.4 Relationships between supporting data and KPIs

KPIs / Data	WE	AR	TR	AE	UE	OEE	NEE	A	E	QR	SeR	TE	PR	SQR
PBT				-*		-*	-*	-*						
PRI						+*	+*		+*					
APWT	+*													
AUPT		+	-	+	-		+*	+	-		-*	-		
AUBT		+*	-	+*	-*			+	-					
AOET		-*	-*	+				+	-				-*	
APAT	-*													
APT		+	-	+	+*		-*	+*	-*		-	+*	+*	
ADET			-	+	-							-*	-	
AUST		+	-	+	-		+				+*		-	
ATT		-	-										-	
AQT		-	-										-	
SQ			+						+	-				+*
PSQ														-*
GQ			+			+*	+*		+	+*				
RQ			+						+	-				
PQ			+*			+	+		+*	-*				+
POT				-		-	-	-						

Table 4.5 Relationships between supporting data and KPIs (continuation of Table 4.4)

KPIs / Data	FPY	SR	RR	FR	Cm	Cmk	Cp	Cpk	MTBF	MTTF	MTTR	CMR
SQ		+*	-	+								
GQ		-	-	-*								
RQ		-	+*	+								
PQ		-*	-*	+*								
TTF										+*		
TBF									+*			
TTR											+*	
FE									-*	-*	-*	
CMT												+*
PMT												-*
GP	+*											
IP	-*											
USL					+*	+*	+*	+*				
LSL					-*	-*	-*	-*				

- Step III: Evaluate the impact of this transformation solution on the legacy system according to trends in these affected KPIs

In order to evaluate the impact of this transformation solution on legacy systems and prove that it brings benefits, we need to know under what trends KPIs changes can benefit legacy systems. Therefore, according to ISO 22400-2, the meanings of KPIs and their better trends are summarized in Table 4.6.

With a clear understanding of what trends in KPIs can benefit legacy systems, it is able to evaluate the impact of this transformation solution on the legacy system. For example, if in the previous step we identify that the affected KPI is UE and its value increases. According to Table 4.6, the higher the value of UE, the better. Therefore, it can be concluded that this transformation solution will bring benefits to the legacy system because the increase in UE represents an increase in the productivity of workstations.

Table 4.6 Description of KPIs and their better trend (summarized from (ISO 22400–2, 2014))

Name of KPIs	**Description of KPIs**	**Better trend of KPIs**
Worker Efficiency (WE)	WE considers the relationship between the actual personnel work time related to production orders and the actual attendance time of the employee.	The higher, the better
Allocation Ratio (AR)	AR shows how much of the throughput time of a production order is caused by actual processing. Its value may exceed 100% because of overlapping production operations.	The higher, the better
Throughput Rate (TR)	TR is an index for evaluating the efficiency in production.	The higher, the better
Allocation Efficiency (AE)	AE indicates how strongly the planned capacity of the production system is already used and how much planned capacity is still available.	The higher, the better
Availability (A)	A is called the degree of utilization or capacity factor. It indicates how strongly the capacity of the production system is used in relation to the available capacity. Although both AE and A are used to characterize the capacity, the percentage of A is lower than that of AE in the same production system. This difference is due to the fact that AE is only affected by the time required for transfer and queuing operations, while A also takes into account the downtime.	The higher, the better
Utilization Efficiency (UE)	UE indicates the productivity of workstations.	The higher, the better
Technical Efficiency (TE)	Similar to UE, TE also indicates the productivity of workstations. However, in contrast to UE, TE does not include setup time.	The higher, the better
Effectiveness (E)	E indicates how effective the assembly line is during the production time.	The higher, the better
Overall Equipment Effectiveness index (OEE)	OEE forms the basis for improvements by better production information, identification of production losses, and improvement of the product quality by optimized processes.	The higher, the better
Net Equipment Effectiveness (NEE)	Similar to OEE, NEE is also a comprehensive indicator and is used in a wide range of industry sectors. In contrast to OEE, NEE considers the setup time.	The higher, the better
Quality ratio (QR)	QR is the ratio between the good quantity and the produced quantity.	The higher, the better

Name of KPIs	Description of KPIs	Better trend of KPIs
Production process ratio (PR)	PR is an index for the efficiency of production. A low value of PR indicates that the production orders include a lot of wait-time or idle periods instead of production time.	The higher, the better
The Setup Ratio (SeR)	SeR indicates the relative loss of value-adding opportunities for the work unit. For the manufacturing industry, a high setup ratio means the consumption of value-added time.	The lower, the better
Actual to planned scrap ratio (SQR)	SQR is used as a short-term indicator to improve production as well as a tool to control the planning value in the ERP. A low value indicates that less scrap is produced than expected. On the other hand, a constant low value indicates that the planned scrap ratio is too high. This might result in unnecessary material allocation. SQR is specified in the ERP system in order to ensure the necessary material allocation.	The lower, the better
Scrap ratio (SR)	SR is the relationship between the scrap quantity and the produced quantity.	The lower, the better
Rework ratio (RR)	RR is the relationship between the rework quantity and the produced quantity.	The lower, the better
Fall off ratio (FR)	FR is typically used in concatenated processes, where a product is produced in the first manufacturing step but may have scrap in further operations. This indicator has an influence on the planned scrap and on the production quality per manufacturing step as well as material wastage.	The lower, the better
First pass yield (FPY)	FPY designates the percentage of products, which fulfills the quality requirements in the first process run without reworks (good parts).	The higher, the better
Machine capability index (Cm)	Cm indicates the ability of a machine or a work mechanism to produce the specified quality for a specific characteristic. It is the relationship between the dispersion of a process and the specification limits. The machine capability value is usually specified by customer requirements. Typical value is Cm> 1.67.	The higher, the better
Critical machine capability index (Cmk)	Similar to Cm, Cmk also indicates the ability of a machine or a work mechanism to produce the specified quality and the typical value is Cmk >1.67. In contrast to Cm, Cmk is also related to averages of the specification limits.	The higher, the better
Process capability index (Cp)	Cp should indicate based on statistic methods as soon as possible if the production process will produce the product according to the committed quality specifications. A process is usually called capable if the Cp >1.33.	The higher, the better

Name of KPIs	Description of KPIs	Better trend of KPIs
Critical process capability index (Cpk)	Similar to Cp, Cpk should also indicate based on statistic methods as soon as possible if the production process will produce the product according to the committed quality specifications. In contrast to Cp, Cpk is also related to averages of the specification limits.	The higher, the better
Mean operating time between failures (MTBF)	MTBF is an indicator of expected system reliability calculated on a statistical basis from the known failure rates of various components of the work unit. It represents the expectation of the operating time between failures. It is a statistical approximation of how long a work unit should last before failure.	The higher, the better
Mean time to failure (MTTF)	Similar to MTBF, MTTF is also an indicator of expected system reliability. It represents the expectation of the time to failure. MTTF is used for both non repaired items and repairable items. It is equivalent to MTBF in case of a non-repairable work unit.	The higher, the better
Mean time to repair (MTTR)	MTTR is the average time that an item required to restore a failed component in a work unit. It represents the expectation of the time to repair.	The higher, the better
Corrective maintenance ratio (CMR)	CMR gives the idea of the time spent in corrective tasks on work units compared with the whole maintenance time. This ratio shows the lack of system reliability and therefore should be minimized.	The lower, the better

② Qualitative analysis:

For qualitative analysis, we extract the characteristics of CPPSs from the literature we reviewed in Chapter 2 as the evaluation characteristics, categorize them into three dimensions (i.e., technological, informational and organizational dimensions), and propose some evaluation topics to interpret these characteristics, as shown in Table 4.7. We cannot guarantee that these evaluation characteristics are complete, but only list those frequently mentioned. Some of these evaluation topics can be directly linked to object classes. For example, the evaluation topic "TE1" can be linked to the object classes "Machine". In this way, once we obtain that the object class to be added or modified is "Machine", we can directly locate to TE1 to evaluate the impacts of the transformation solution on the legacy system. However, some evaluation topics are not explicitly associated with specific object classes, and they may be affected by multiple classes, which requires people to analyze the specific case based on experience.

Table 4.7 Evaluation characteristics and topics of the qualitative analysis

Evaluation dimensions	Evaluation characteristics	Evaluation topics (TE: technological evaluation, IE: informational evaluation, OE: organizational evaluation)
Technological dimension	Connectivity (Monostori et al., 2016)	TE1: How is the connectivity of Machine in the shop floor?
	Intelligence (Monostori et al., 2016)	TE2: What about the intelligence of Product?
	Security (Toublanc et al., 2017)	TE3: Do elements in the shop floor have a security mechanism?
	Automation control	TE4: Is automation control of production processes available?
	Reconfiguration capability (Otto et al., 2018)	TE5: How is the reconfiguration performed?
	Upgrading/evolution capability (Cachada et al., 2018)	TE6: How do upgrading solutions influence the actual production?
	Virtualization capability (Babiceanu & Seker, 2016)	TE7: Does the shop floor use simulation tools to virtualize the production processes?
	Data acquisition capability (Silva et al., 2017)	TE8: How is data collected?
	Data storage capability (Marini & Bianchini, 2016)	TE9: How is data stored?
	Data analysis capability (X. Xu & Hua, 2017)	TE10: Is there any model or tool used for data analysis?
Informational dimension	Accessibility of information (Constantinescu et al., 2015)	IE1: Are there specific APIs that allow other systems to connect to data and information? IE2: How is information presented to humans?
Organizational dimension	Functions provided in the system	OE1: How is monitoring performed? OE2: How is quality inspection performed? OE3: How is maintenance performed? OE4: How is production scheduling performed? OE5: How is diagnostic performed? OE6: How is performance analysis performed?
	Decision-making capability	OE7: What models or tools are used for making decisions?
	Human skills	OE8: To what extent are humans equipped with the relevant skills for Industry 4.0?

Some options for the evaluation topics are proposed as follows.

- For technological evaluation #1 (How is the connectivity of Machine in the shop floor?):
  - Machine is controlled by humans and does not have any connectivity capabilities.
  - Machine is controlled by PLC that belongs in a local industrial network.
  - In addition to the connectivity of local industrial network, Machine also provides a vendor-specific API that allows other systems to integrate with it.
  - Machine is networked via standardized mechanisms and exposes standard API (e.g., OPC UA and MQTT).
- For technological evaluation #2 (what about the intelligence of Product?):
  - The product has no intelligence.
  - The product has some kind of intelligence by being equipped with the identification technology, such as Barcodes and RFID tags.
  - The product has full intelligence because sensors and actuators are attached to the product. In this way, production data can be read from the product directly.
- For technological evaluation #3 (do elements in the shop floor have a security mechanism?):
  - No.
  - Part of security mechanisms.
  - Full security mechanisms.
- For technological evaluation #4 (is automation control of production processes available?):
  - The control exists in each Machine, but central control is not available.
  - The production control is managed from a centralized system (e.g., SCADA).
  - The production control is managed from an EIS system (e.g., MES).
  - The production control is managed from the cloud
- For technological evaluation #5 (how is the reconfiguration performed?):
  - Reconfiguration is performed manually by humans. During this process, the production much stop, so it is time-consuming.
  - Reconfiguration is performed locally by tools and software in HMIs.
  - Reconfiguration is performed automatically by centralized tools (e.g., SCADA).
- For technological evaluation #6 (how do upgrading solutions influence actual production?):
  - The automation systems architecture is centralized. Changes to the system make the system offline (i.e., the production stops) until the upgrading is completed.

- The system is modular-based and decentralized and can run multiple versions in parallel. Therefore, the production never stops, even when the upgrade is taking place.

➢ For technological evaluation #7 (does the shop floor use simulation tools to virtualize the production processes?):

- There are no virtualization tools
- The simulation software is used.
- The digital twin is built.

➢ For technological evaluation #8 (how is data collected?):

- There are no data acquisition devices and technologies. The acquisition of data is performed by humans.
- Some devices have connectivity capabilities and protocols (e.g., serial cables and LAN/WAN) for automatic data acquisition.
- All devices have connectivity capabilities that allows the acquisition of real-time data.

➢ For technological evaluation #9 (how is data stored?):

- The data is stored in papers.
- The data is stored in a central data repository (e.g., database or cloud).
- Part of data is stored in local systems and the rest is stored centrally in data repository (e.g., database or cloud).

➢ For technological evaluation #10 (is there any model or tool used for data analysis?):

- No models or tools used for data analysis
- Very simple models are available but their usability is based on humans' experience.
- Advanced models and tools are available, such as AI.

➢ For informational evaluation #1 (are there specific APIs that allow other systems to connect to data and information?):

- No.
- There are custom interfaces.
- Each EIS has access to data and information through well-defined APIs.

➢ For informational evaluation #2 (how is information presented to humans?):

- By papers.
- By control panels.
- By IoT devices.

➢ For organizational evaluation #1 (how is monitoring performed?):

- There is no monitoring system and it is performed by humans.
- It is performed through a central supervisory system (SCADA).

- It is performed through EISs software.

➢ For organizational evaluation #2 (how is quality inspection performed?):
- The quality inspection is performed by humans.
- There are automated quality inspection modules in critical points of the production system.
- There is a fully automated quality inspection system that monitors every stage of production.

➢ For organizational evaluation #3 (how is maintenance performed?):
- The maintenance plan is defined based on the experience of humans.
- The maintenance plan is defined automatically by the system based on historical data for reactive or preventive maintenance.
- The maintenance plan is defined automatically by the system based on real-time data for reactive or preventive maintenance.

➢ For organizational evaluation #4 (how is production scheduling performed?):
- The production schedules are made by humans.
- The production schedules are generated by EISs software (e.g., MRP and ERP).

➢ For organizational evaluation #5 (how is diagnostic performed?):
- No diagnostic service.
- The diagnostic analysis is performed by humans occasionally. There is no standard procedure, and it is strongly dependent on the experience of humans.
- Standard procedures are defined for problem identification and root causes identification. Furthermore, the effectiveness of the solutions adopted is monitored to ensure continuous improvement.

➢ For organizational evaluation #6 (how is performance analysis performed?):
- There are rudimentary tools for performance analysis, e.g., analysis of average values.
- There are analytical tools for the performance analysis based on the historical data.
- There are advanced analytical tools combined with simulation models for performance analysis.

➢ For organizational evaluation #7 (what models or tools are used for making decisions?):
- Deterministic model (linear programming, network model, etc.), stochastic model (Markov process model, simulation model, decision trees/game theory), forecasting and statistical models, other models (MCDM Models, AHP, Visual interactive modeling, etc.).

- AI tools (neural networks, rule-based, knowledge-based, case-based reasoning, genetic algorithm, and fuzzy logic systems, ML, DL).

➢ For organizational evaluation #8 (to what extent are humans equipped with the relevant skills for Industry 4.0?):

- Lack of related skills for Industry 4.0.
- Digital skills, troubleshooting skills, analytical skills, problem-solving skills and communication skills.
- Cutting-edge analytical skills, cognitive skills (problem analysis, learning, knowledge building, etc.) and social skills (participation, communication, cooperation, etc.).

4.4 Conclusion

A method based on the meta-model is proposed for the transformation of an existing production system with its integrated EISs into a CPPS. This method defines the transformation steps in a top-down manner, starting with the analysis of the existing system, moving to the definition of the target system requirements, then going deeper to the gap analysis to give a specific transformation solution, and finally to the evaluation of the transformation solution. The final result of this method is a transformation matrix which is a useful tool to guide industry practitioners to understand the current status of existing production systems and to visualize which elements need to be added and modified to become a real CPPS. In this way, the traditional production systems will be smoothly transformed to CPPSs by implementing instantiating these object classes one-by-one. Furthermore, in order to evaluate the benefits obtained from the transformation solution before further development of it, two kinds of analysis are introduced: quantitative and qualitative analyses. A three-step quantitative analysis process is proposed, which is based on standardized KPIs that defined by the international standard ISO 22400. The qualitative analysis is performed through illustrative information from three dimensions: technological, informational and organizational dimensions. This evaluation supports manufacturers to understand whether their expected benefits are achieved, and if not, a new transformation solution can be redesigned before further deployment of the original solution to avoids risks.

Chapter 5: Case study

Abstract

The goal of this chapter is to explain how to use the method proposed in Chapter 4 and to demonstrate the efficacy and general applicability of this method. Firstly, a simulation-based case is built in Simio (a simulation software). After performing the transformation process, a transformation matrix that presents possible improvements to the As-Is system is obtained and the performance of the To-Be scenario is evaluated through quantitative and qualitative analyses. It can be found that this To-Be scenario will bring many benefits to the legacy system and it deserves to be implemented. After implementing the To-Be scenario in Simio, we calculate KPIs to validate the usefulness of this method. Then, a lab case located in the IUT de Nantes is introduced. By applying the proposed method, the obstacles of this lab case are identified, the To-Be system requirements are defined and a To-Be solution is proposed. As the To-Be solution of this lab case has not been implemented, its benefits are only predicted through quantitative and qualitative analyses.

5.1 Introduction

To demonstrate the efficacy and general applicability of our method, we apply it to two application scenarios: i) a simulation-based case study built in Simio, which avoids the high efforts of implementation in the real factory. Although this is a hypothetical simulation and its results do not have any practical value, it is enough to demonstrate the usefulness of the proposed method. ii) a lab-based case study, which is an automated assembly line located in the IUT de Nantes.

The rest of this chapter is organized as follows: Section 5.2 clarifies each step of applying the transformation method on the simulation case and Section 5.3 clarifies each step of applying the transformation method on the lab case. In both cases, transformation solutions are proposed and the quantitative and qualitative analyses are performed to evaluate the potential benefits that can be obtained from the transformation.

5.2 Simulation-based case

5.2.1 Transformation step I: understand the As-Is system

In this section, we build an assembly line in Simio, which mainly consists of four workstations. We assume that each workstation is equipped with a robotic arm to perform assembly operations and that each robotic arm is equipped with a camera to sense the product to be handled. The layout of this assembly line is shown in Figure 5.1.

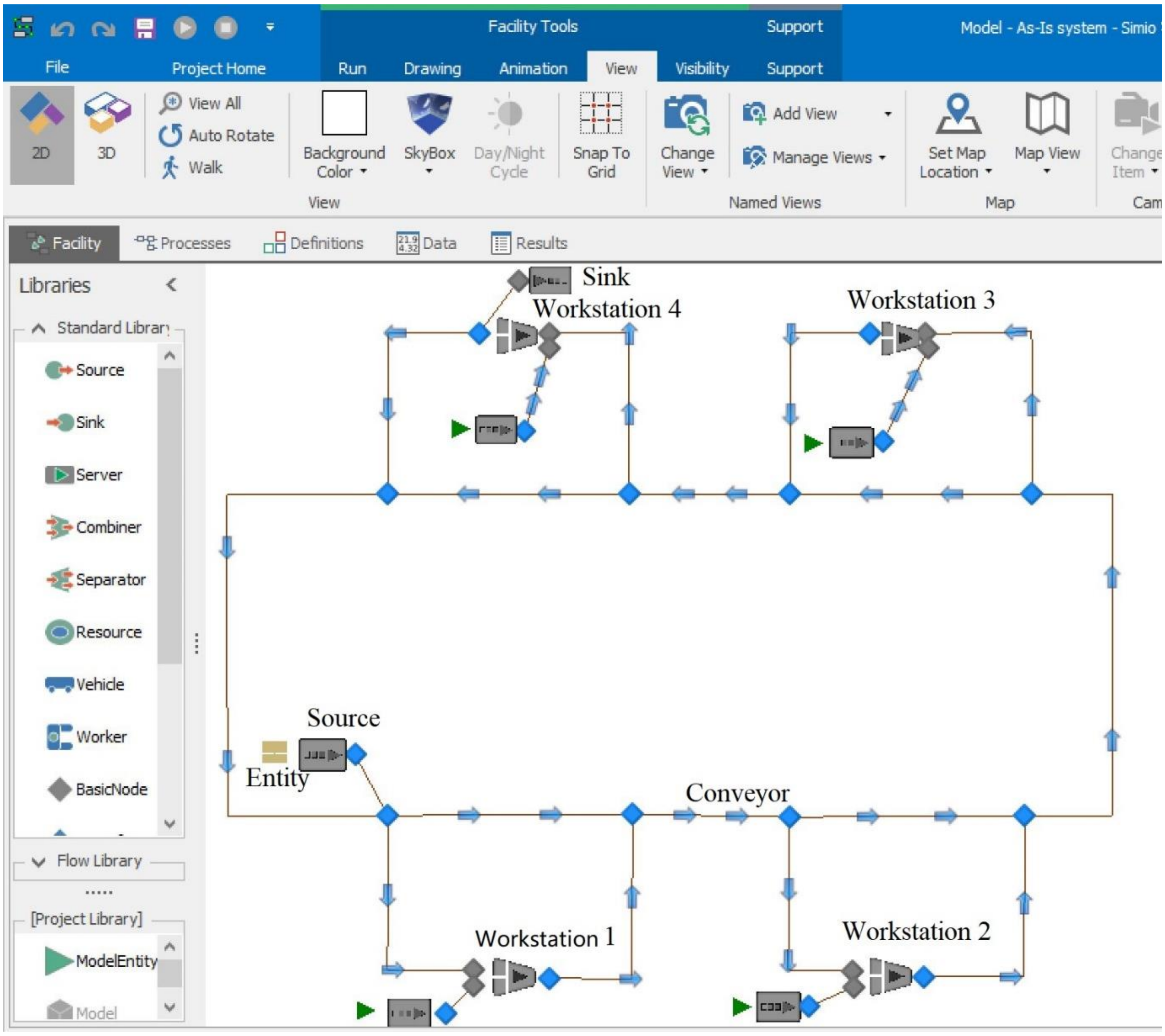

Figure 5.1 Layout of the As-Is system model in Simio

The main features of the model are explained as follows:

- **Model structure**. The structure of the model relies mainly on the use of predefined objects in Simio. The objects that we used in Simio are:
  - Source object. The main purpose of this object is to create entities and set the number of entities to be created each time. In our simulation, this object is used for generating products.
  - Combiner object. This object is characterized mainly by three properties: batch quantity, capacity, and processing time. The batch quantity restricts the number of member entities attached to a parent entity and the capacity restricts the number of entities that can be processed simultaneously. In our simulation, this object is used to represent the assembly workstation.
  - Sink object. This object represents the end of the system operations. When entities enter this object, they are automatically destroyed.

- Nodes and links. These objects are usually used for connecting objects. In the nodes and links, different properties can be set, such as direction and maximum speed. In our simulation, this object is used to represent the conveyor network.

- **Model parameters (**system configuration-related parameters**).** These parameters are static, in the sense that they are set before the simulation is run and they cannot be changed when the simulation is running. In the following, the main static parameters are listed:
  - *List of assembly tasks that can be performed by each workstation.*
  - *Processing time of each workstation.*
  - *Setup time of each workstation.*
  - *Input queue capacity of each workstation* (considering that each workstation has a product input storage area with limited capacity).
- **Input data**
  - *Number of orders.*
  - *Assembly recipe of each product.*
  - *Assembly sequence*, i.e., which products are assembled by which workstations. This could be imported from MES.
  - *Planned time: PBT*, *PRI.*
- **Model constraints**
  - Constraint 1: One workstation can process one operation at a time.
  - Constraint 2: Each machine has a limited queue capacity. No more operations than this queue capacity can wait in the queue.
  - Constraint 3: The first job arriving in the queue is the first treated, i.e., First In First Out (FIFO) rule.

After completing the configuration of the model, it is able to run. The assembly line operates according to the previously input assembly sequence until the predefined order quantity is completed. However, during the running process, it can be found that this assembly line does not implement the connectedness of all the elements within the industrial network, which results in the inability to obtain information from the surrounding environment and to respond to internal and external changes.

5.2.2 Transformation step II: define the To-Be system requirements

According to the problems identified in the As-Is system in step I, the requirement for the To-Be system is defined:

- The connectedness of products and workstations within an industrial network.

In this case, products can acquire information from their environment (e.g., capabilities and states about workstations and their current assembly progress), communicate with workstations for data sharing, and decide assembly sequences autonomously, so that the To-Be system can avoid unplanned downtimes of workstations.

5.2.3 Transformation step III: gap analysis through instantiating the meta-model

At the C1 level, according to Figure 4.2, we first map the As-Is system with the classes extracted from the C1 level of the 5C architecture. The result is shown in Table 5.1. Then, these object classes are checked one by one to see if the To-Be system requirements can be met by new instantiations of these object classes. To enable the connectedness of products and workstations within the industrial network, RFID technologies are suitable for giving products and workstations the ability to store, acquire and communicate data. Therefore, the existing instantiation of the class “Data acquisition technology”, “Data storage technology” and “Raw data” that are extracted from the 5C architecture need to be modified. According to Table 3.3, this level only has technological and informational relationships. Next, we map the As-Is system with the classes extracted from the enterprise modeling standards that are associated with the technological and informational relationships at this level, i.e., the instantiation of the “Capacity” as shown in Table 5.1. As the existing instantiations of the object classes “Data acquisition technology” and “Data storage technology” need to be modified, the instantiation of classes “Capability” needs to be modified accordingly. Since the To-Be system requirement is able to be met at the C1 level, the instantiation process stops at this level. The transformation matrix is shown in Table 5.1.

Table 5.1 Transformation matrix of object classes in the simulation case

<table>
<tr><th colspan="2" rowspan="2">Object classes</th><th colspan="2">Instantiation of object classes</th><th colspan="3">States of object classes</th></tr>
<tr><th>As-Is system</th><th>To-Be system</th><th>To be created</th><th>To be modified</th><th>No modification</th></tr>
<tr><td rowspan="15">C1 level</td><td>Product</td><td colspan="2">Assembled part and finished product</td><td></td><td></td><td>✓</td></tr>
<tr><td>Actuator</td><td colspan="2">Robot end effector</td><td></td><td></td><td>✓</td></tr>
<tr><td>Sensor</td><td colspan="2">Camera</td><td></td><td></td><td>✓</td></tr>
<tr><td>Machine</td><td colspan="2">Robotic arm, Conveyor</td><td></td><td></td><td>✓</td></tr>
<tr><td>Controller</td><td colspan="2">PLC of robotic arm</td><td></td><td></td><td>✓</td></tr>
<tr><td>Communication Protocol</td><td colspan="2">Ethernet</td><td></td><td></td><td>✓</td></tr>
<tr><td>EIS software package</td><td colspan="2">MES</td><td></td><td></td><td>✓</td></tr>
<tr><td rowspan="2">Data Acquisition Technology</td><td colspan="2">• Hardware: PLC, computer
• Software: computer program</td><td rowspan="2"></td><td rowspan="2">✓</td><td rowspan="2"></td></tr>
<tr><td>-</td><td>RFID reader</td></tr>
<tr><td rowspan="2">Data Storage Technology</td><td colspan="2">• Hardware: computer
• Software: MES database</td><td rowspan="2"></td><td rowspan="2">✓</td><td rowspan="2"></td></tr>
<tr><td>-</td><td>RFID tag</td></tr>
<tr><td rowspan="2">Raw Data</td><td colspan="2">Data from PLC and MES</td><td rowspan="2"></td><td rowspan="2">✓</td><td rowspan="2"></td></tr>
<tr><td>-</td><td>Data from RFID readers and tags</td></tr>
<tr><td colspan="6" style="display:none"></td></tr>
<tr><td colspan="6" style="display:none"></td></tr>
<tr><td rowspan="2">EISs</td><td rowspan="2">Capability</td><td colspan="2">Data acquisition and storage capability</td><td rowspan="2"></td><td rowspan="2">✓</td><td rowspan="2"></td></tr>
<tr><td>-</td><td>New data acquisition and storage capability brought by the RFID technology</td></tr>
</table>

For this transformation solution, the main improvement is that each product and workstation is equipped with RFID tags and RFID readers. The assembly process of the To-Be system will be as follows:

Firstly, the order-related data are written into the RFID tag of products when they come to the assembly line, including the recipe of each product, the number of products to be produced, etc. At the same time, each workstation has a list of operations it is able to perform. Therefore, when the product arrives at the entrance of a workstation, the RFID reader reads the operation pointer to know the progress of the product and compare the next operation of the product with the list of operations that the workstation can perform. If the operation to be done is part of the operations that can be done on this workstation, and if the workstation management rule allows accepting it, then the product is transferred to the storage area of the workstation. Once entering the workstation, it executes the operation needed by the product and the data is read on the RFID tag. Finally, after the operation is completed, there is an RFID writer unit that can update the progress of the product. Therefore, the assembly process will be autonomous, where products could communicate with workstations to decide their next operations.

Compared to the As-Is system, in the To-Be system, the operators have no involvement in the decision-making process. It is the product's progress along the assembly system that will lead to decisions.

5.2.4 Transformation step IV: evaluation of the transformation solution

(1) Quantitative analysis

According to Figure 4.4, there are three steps to conduct the quantitative analysis for evaluating the transformation solution as follows.

- Step I: Identify which supporting data will be affected by the object classes that need to be modified and added based on the transformation matrix

According to the transformation matrix in Table 5.1, the object classes that need to be modified are “Data acquisition technology”, “Data storage technology”, “Raw data” and “Capability”. The result of new instantiations of these classes in the To-Be system is to make the assembly process autonomous. This has the advantage of avoiding performing a production scheduling before a production starts and of being totally reactive more robust to disruptions. In other words, if a workstation breaks down, the assembly process will continue without causing downtime, which is achieved through real-time communication between products and machines. Therefore, this transformation solution will affect time-related supporting data. Since the purpose of modifying these object classes is to reduce downtime, the value of the supporting data “ADET” will decrease.

- Step II: Identify the affected KPIs according to the relationships between KPIs and their supporting data and analyze trends in these KPIs

According to the relationships between KPIs and their supporting data in Table 4.4, there are 5 KPIs that are affected by ADET, namely TR, AE, UE, TE and PR, of which only AE has a positive relationship with ADET, while the remaining four KPIs have negative relationships with ADET. Therefore, when the value of ADET decreases, the values of TR, UE, TE and PR will increase, but the value of AE will decrease.

- Step III: Evaluate the impact of this transformation solution on the legacy system according to trends in these affected KPIs.

According to Table 4.6, TR and PR are used for evaluating the efficiency of the production, and UE and TE are used for evaluating the productivity of workstations. So, the higher their value, the better they are. And according to the results obtained in the previous step, i.e., the values of TR, UE, TE and PR will increase, which indicates that the efficiency of the production and the productivity of the workstation will increase. Another result obtained in the previous step is that the value of AE will decrease, but the higher its value, the better. AE indicates how strongly the planned capacity of the production system is already used and how much planned capacity is still available. Therefore, if the manufacturer values productivity and efficiency more, then this transformation solution is feasible. But if the manufacturer values the planning capacity of the production system more, then this transformation solution is unfeasible, and a new transformation solution needs to be designed.

Through this evaluation, the manufacturer can avoid risks by determining in advance whether to implement this transformation solution.

(2) Qualitative analysis

Quantitative indicators may not be sufficient, whereas the qualitative analysis that can produce in-depth and illustrative information is performed. According to the evaluation topics proposed in Table 4.7, qualitative analysis is shown in Table 5.2.

Table 5.2 Qualitative analysis of the simulation case

Evaluation dimensions	**Evaluation characteristics**	**As-Is system**	**To-Be system**
Technological dimension	Connectivity	Machine is connected by PLC within a local industrial network. But the connectivity of the product is not available.	Both Machine and Product are connected within the industrial network.
	Intelligence	The product has no intelligence.	The product has intelligence because it can acquire information from its environment through RIFD technologies.
	Data acquisition capability	Only data related to Machine and production processes is collected.	Data related to Machine and Product is both collected, as well as the data of production processes.
	Data storage capability	All data is stored in the central MES database.	Part of the data is stored in RFID and the rest is stored centrally in the MES database.
Organizational dimension	Functions provided in the system	No autonomous scheduling.	Autonomous scheduling is enabled by the negotiation between products and machines.

5.2.5 Simulation results of the To-Be system

For the To-Be system, the layout has not changed at all and remains as shown in Figure 5.1, but some features of the model need to be modified. Firstly, in terms of the input data, there is no need to input the assembly sequence. Then, for implementing the communication between products and workstations, some decision logics are added to nodes of the conveyor in Simio:

- Decision rules of the product for entering the workstation:
  - The assembly recipe for the product has not yet been completed.
  - The workstation is in good operating condition, i.e., no breakdown.
  - The input queue capacity of the workstation is not full.
  - This workstation has the least waiting time.

In order to validate the benefits brought by the transformation from the As-Is into the To-Be system, two scenarios are assumed as follows:

- Scenario #1: A minor failure. One of the redundant workstations becomes unavailable due to some minor failures, such as the blockage of the input queue of the workstation. Because this failure is not a big problem, it can be solved in a short period of time after it has been detected by humans. Therefore, there is no need to reschedule the assembly sequence in the As-Is system, but there will be a short downtime. While in the To-Be system, there is no downtime.
- Scenario #2: A major failure. At a given time, one of the redundant workstations breaks down. Because this failure will take a long period of time to resolve, the assembly sequence has to be rescheduled in the As-Is system, which will cause a period of downtime for the entire assembly line. In contrast, there is no downtime in the To-Be system, as it allows autonomous scheduling to find a suitable replacement workstation to continue production.

Since failures are intentionally introduced into the system to observe behaviors of systems, some failure-related parameters should be specified both in the As-Is and To-Be system:

- Failure-related parameters
  - *The time from the appearance of the minor failure to its detection by humans.*
  - *The time from humans detecting the minor failure to solving it.*
  - *The time from the appearance of the major failure to its detection by humans.*
  - *The time for rescheduling the assembly sequence in the As-Is system in the event of a major failure.*

After simulating these two scenarios both in the As-Is and To-Be system, the five affected KPIs that are identified in step IV are calculated and their values are shown in Table 5.3. It can be seen that in both scenarios, the real trends of these KPIs are the same as the results of the previous quantitative analysis, which proves the feasibility of our method.

Table 5.3 Values of KPIs in the As-Is and To-Be systems

KPIs	Scenario #1		Scenario #2	
	As-Is system	To-Be system	As-Is system	To-Be system
TR (piece/s)	0.03	0.04	0.027	0.032
AE	84.69%	81.67%	38.07%	25.47%
UE: UE1- workstation #1 UE2- workstation #2 UE3- workstation #3 UE4- workstation #4	UE1=74.69% UE2= 82.15% UE3=79.04% UE4= 75.01%	UE1=94.54% UE2= 93.44% UE3= 88.37% UE4= 95.08%	UE1=51.75% UE2= 56.31% UE3= 31.2% UE4= 51.75%	UE1=94.54% UE2= 93.44% UE3= 66.72% UE4= 95.32%
TE TE1- workstation #1 TE2- workstation #2 TE3- workstation #3 TE4- workstation #4	TE1=78.68% TE2=85.8% TE3=82% TE4=78.96%	TE1=100% TE2=100% TE3=92.2% TE4=100%	TE1=53.15% TE2=58% TE3=32.21% TE4=53.15%	TE1=100% TE2=100% TE3=69.02% TE4=100%
PR	243%	350%	234%	281%

5.3 Lab case

5.3.1 Transformation step I: understand the As-Is system

This case is an automated assembly line located in the IUT de Nantes (Cardin, 2016), as shown in Figure 5.2.

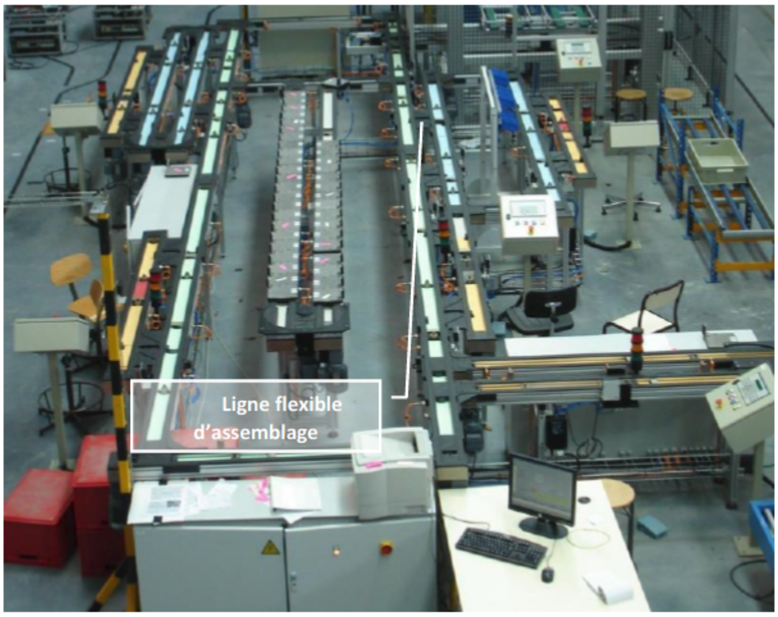

Figure 5.2 The assembly line in the IUT de Nantes (Cardin, 2016)

This assembly line includes six workstations, a pallet storehouse and transfer loops carried out by belt conveyors. At station 1, a Cartesian robot is used to load or unload the pallet. Stations 2, 3 and 5 are used to deposit the assembled parts. Station 4 is an automated vision-based quality control station, while station 6 is a manual station allowing for product rework in case it is not possible to do so automatically. Pallets transport the products and each of them is equipped with an RFID tag that stores a list of services needed to be performed on the transported products. At each switching point on the conveyor belt, RFID read/write units can determine the direction of the pallets. This assembly line is controlled by four PLCs arranged on an Ethernet field network. Control panels are placed in front of each workstation for direct communication between operators and PLCs. They are connected to the PLCs by a serial link. 18 modules for reading/writing electronic tags are placed on a FipIO network, of which the PLCs are part. The MES is also located on the Ethernet network. The MES consists only of a Microsoft SQL Server database and a supervision application built on Wonderware Intouch. The monitored information is visualized in HMIs for humans to make decisions and take action.

It can be seen that the As-Is system has a good automation degree to execute production planning and quality control. The data acquisition is performed on the internal network using a serial cable. However, there is no data analysis technology to detect disruptions.

5.3.2 Transformation step II: define the To-Be system requirements

Disruptions are mainly caused by internal factors, related to tangible assets of production systems, e.g., tool breakages and machine breakdowns (Suwa & Sandoh, 2012) and can happen at any time, which hinder the achievement of production objectives. Therefore, the requirements of the To-Be system are defined as follows:

- Requirement #1: add the predictive maintenance function to detect disruptions.
- Requirement #2: notify maintainers to take repair actions through IoT devices (e.g., smartwatches, smartphones, smart glasses).

5.3.3 Transformation step III: gap analysis through instantiating the meta-model

At the C1 level, after the four mapping activities between the As-Is system and the meta-model, the instantiations of object classes at this level are obtained, as shown in Table 5.4 and Table 5.5. No object class can be instantiated to meet To-Be system requirements, so the instantiation process goes to the C2 level.

At the C2 level, the process is the same as at the C1 level and no class can be instantiated to meet To-Be system requirements, so the instantiation process goes to the C3 level.

At the C3 level, we first map the As-Is system with the classes extracted from the 5C architecture. Then, these object classes are checked one by one to see if the To-Be system requirements can be met by new instantiations of these object classes. Requirement #1 involves predictive maintenance function. To enable this, the instantiation of the object class “Data analysis technology” could be created. Several data analysis methods have been proposed for diagnosis and maintenance in literature, such as mathematical modeling, simulation-based techniques and AI tools. In addition, the instantiation of the object class “Information” also needs to be modified in order to show abnormal alarms of possible failures. According to Table 3.3, this level only has technological relationships. Next, we map the As-Is system with the classes extracted from the enterprise modeling standards that are associated with the technological relationships at this level, i.e., the instantiation of the “Capacity” as shown in Table 5.4. As the existing instantiations of the object classes “Data analysis technology” need to be created, the instantiation of classes “Capability” needs to be modified accordingly. As requirement #2 has not been met yet, the transformation process goes to the C4 level.

At the C4 level, we first map the As-Is system with the classes extracted from the 5C architecture. Then, these object classes are checked one by one to see if requirement #2 can be met by new instantiations of these object classes and we find that it could be met by the instantiation of the class “Presentation interface”. To be specific, IoT devices, such as connected watches, smartphones and virtual reality tools, can be used to transmit maintenance recommendations to humans. Next, we map the As-Is system with the classes extracted from the enterprise modeling standards that are associated with the technological relationships at this level, i.e., the instantiation of the "Resource". As the instantiation of the object class "Presentation interface" needs to be modified, the instantiation of the object class "Resource" will need to be modified accordingly. Since all To-Be requirements are able to be met at the C4 level, the instantiation process stops at this level.

Table 5.4 Transformation matrix of object classes extracted from the 5C architecture

<table>
<tr><th colspan="2" rowspan="2">Object classes</th><th colspan="2">Instantiation of object classes</th><th colspan="3">States of object classes</th></tr>
<tr><th>As-Is system</th><th>To-Be system</th><th>To be created</th><th>To be modified</th><th>No modification</th></tr>
<tr><td rowspan="10">C1</td><td>Product</td><td colspan="2">Assembled part and finished product</td><td></td><td></td><td>✓</td></tr>
<tr><td>Actuator</td><td colspan="2">Robot end effector</td><td></td><td></td><td>✓</td></tr>
<tr><td>Sensor</td><td colspan="2">Camera</td><td></td><td></td><td>✓</td></tr>
<tr><td>Machine</td><td colspan="2">Robotic arm, Conveyor</td><td></td><td></td><td>✓</td></tr>
<tr><td>Controller</td><td colspan="2">PLC</td><td></td><td></td><td>✓</td></tr>
<tr><td>Communication Protocol</td><td colspan="2">Ethernet, Serial cable</td><td></td><td></td><td>✓</td></tr>
<tr><td>EIS software package</td><td colspan="2">MES</td><td></td><td></td><td>✓</td></tr>
<tr><td>Data Acquisition Technology</td><td colspan="2">• Hardware: camera, PLC, RFID reader
• Software: computer program</td><td></td><td></td><td>✓</td></tr>
<tr><td>Data Storage Technology</td><td colspan="2">• Hardware: computer, RFID tag
• Software: SQL database</td><td></td><td></td><td>✓</td></tr>
<tr><td>Raw Data</td><td colspan="2">Data from camera, PLC, RFID reader and MES</td><td></td><td></td><td>✓</td></tr>
<tr><td rowspan="2">C2</td><td>Data Preprocessing Technology</td><td colspan="2">Data suitability assessment, working regime identification and feature extraction algorithm</td><td></td><td></td><td>✓</td></tr>
<tr><td>Meaningful Data</td><td colspan="2">Meaningful feature extracted from raw data</td><td></td><td></td><td>✓</td></tr>
<tr><td rowspan="3">C3</td><td rowspan="2">Information</td><td colspan="2">Production results (e.g., production time of each product)</td><td rowspan="2"></td><td rowspan="2">✓</td><td rowspan="2"></td></tr>
<tr><td>-</td><td>Abnormal alarms of possible failures</td></tr>
<tr><td>Data Analysis Technology</td><td>-</td><td>Real-time synchronous simulation model, AI algorithms for diagnosis</td><td>✓</td><td></td><td></td></tr>
<tr><td rowspan="4">C4</td><td rowspan="2">Presentation Interface</td><td colspan="2">Control panel, Computer</td><td rowspan="2"></td><td rowspan="2">✓</td><td rowspan="2"></td></tr>
<tr><td>-</td><td>IoT devices (e.g., smartphones)</td></tr>
<tr><td>Human</td><td colspan="2">Shop-floor operators and managers</td><td></td><td></td><td>✓</td></tr>
<tr><td>Decision</td><td colspan="2">Maintenance planning and tasks</td><td></td><td></td><td>✓</td></tr>
</table>

Table 5.5 Transformation matrix of object classes extracted from enterprise modeling standards

Object classes		**Instantiation of object classes**		**States of object classes**		
		As-Is system	**To-Be system**	**To be created**	**To be modified**	**No modification**
EIS	Resource	Control panel, Computer, Operator, Manager, MES			✓	
		-	IoT devices			
	Capability	Data acquisition, storage and preprocessing technology			✓	
		-	Data analysis technology			
	Event	Disruptions				✓
	Domain	Maintenance				✓
	Business process	Maintenance planning				✓
	Enterprise activity	Identify failures, define maintenance schedules and assign maintenance jobs				✓
	Person profile	Problem-identification skills and maintenance skills				✓
	Decision center	Human, workstation				✓
	Organizational unit	Maintenance planning department				✓

5.3.4 Transformation step IV: evaluation of the transformation solution

(1) Quantitative analysis

According to Figure 4.4, there are three steps to conduct the quantitative analysis for evaluating the transformation solution as follows.

- Step I: Identify which supporting data will be affected by the object classes that need to be modified and added based on the transformation matrix

According to the transformation matrix in Table 5.1, the object classes that need to be modified and created are “Data analysis technology”, “Presentation interface”, “Information”, “Capability” and “Resource”. The result of new instantiations of these classes in the To-Be system is to detect the disruptions and make predictive maintenance. This has the advantage of avoiding downtime by notifying staff to repair the machine before it breaks down. Therefore, this transformation solution will affect time-related supporting data, including actual time-related data and maintenance time-related data. Since the purpose of modifying and adding these object classes is to reduce downtime and the number of failures, the values of the supporting data “ADET” and “FE” will decrease.

- Step II: Identify the affected KPIs according to the relationships between KPIs and their supporting data and analyze trends in these KPIs

According to the relationships between KPIs and their supporting data in Table 4.4, there are 5 KPIs that are affected by ADET, namely TR, AE, UE, TE and PR, and 3KPIs that are affected by FE, namely MTBF, MTTF and MTTR. For those 5 KPIs that are affected by ADET, only AE has a positive relationship with ADET, and the remaining four KPIs have negative relationships with ADET. For those 3 KPIs that are affected by FE, all have a negative relationship with FE. Therefore, when the value of ADET decreases, the values of TR, UE, TE and PR will increase, but the value of AE will decrease. When the FE decreases, the value of MTBF, MTTF and MTTR will increase.

- Step III: Evaluate the impact of this transformation solution on the legacy system according to trends in these affected KPIs.

According to Table 4.6, TR and PR are used for evaluating the efficiency of the production, UE and TE are used for evaluating the productivity of workstations, and MTBF, MTTF and MTTR are used for evaluating system reliability. So, the higher their value, the better they are. And according to the results obtained in the previous step, i.e., the values of TR, UE, TE, PR, MTBF, MTTF and MTTR will increase, which indicates that the efficiency of the production, the productivity of the workstation and system reliability will increase. Another result obtained in the previous step is that the value of AE will decrease, but the higher its value, the better. AE indicates how strongly the planned capacity of the production system is already used and how much planned capacity is still available. Therefore, if the manufacturer values productivity, efficiency and reliability more, then this transformation solution is feasible. But if the manufacturer values the planning capacity of the production system more, then this transformation solution is unfeasible, and a new transformation solution needs to be designed.

For this lab case, the To-Be system has been partly implemented by (Abdoune, Nouiri, Castagna, et al., 2021) and (Abdoune, Nouiri, Cardin, et al., 2021). They aimed to meet requirement #1, i.e., detection of minor disruptions that happen for a short but frequent time. For this, the digital twin was implemented to model the state of the assembly system and to facilitate the access of real-time data. Also, Logistic Regression (LR) and Artificial Neural Network (ANN) were implemented in python to detect and classify 3 types of minor disruptions: incorrect settings of workstations, minor blocks of the pallets in the turns of conveyors and blocked stops of the pallets in the switch point of conveyors. However, the transformation in the real lab case has so far only been validated by Abdoune, Nouiri, Castagna, et al., (2021) on a small section of the conveyor containing an RFID read/write module, and has not yet been implemented on the entire assembly line. Therefore, we cannot obtain the production data of the entire assembly system to calculate the values of these KPIs.

(2) Qualitative analysis

According to the topics of the qualitative analysis proposed in Table 4.7, the possible transformation benefits of this lab case are shown in Table 5.6.

Table 5.6 Qualitative analysis of the lab case

Evaluation dimensions	Evaluation characteristics	As-Is system	To-Be system
Informational dimension	Data analysis capability	No models or tools used for data analysis	AI algorithms are used to perform data analysis.
	Accessibility of information	Information is only viewed through the control panel in the shop floor.	Through the developed IoT devices, it is possible to view the production information anytime and anywhere.
Organizational dimension	Functions provided in the system	The maintenance plan is defined based on the experience of humans.	Thanks to the AI tool, the maintenance plan is defined automatically by the system based on real-time data for preventive maintenance
	Decision-making capability	There are only simple statistical models that can support humans to make decisions.	AI tools are used to make decisions.

5.4 Conclusion

This chapter describes step by step the use of the proposed method. Different application cases revealed a wide range of applicability of this method. The applications of our methods in simulation-based and lab cases pave the way for further testing in real systems in the future.

Chapter 6: Conclusion

Abstract

This chapter is dedicated to the general conclusion of the presented research contributions and perspectives. Firstly, we revisit the research problems and research gaps identified from the state-of-the-art. Then, we summarize the contributions that have been proposed in this thesis. Finally, we identify potential directions for future research.

6.1 Conclusion

Production systems are no longer rigid, unyielding, and isolated systems anymore. Today, they benefit from some technological innovations: IoT, big data, AI, ICT, CPS, digital twin, cloud, etc. This new situation is shaking up the industry and is considered to be the reason for the emergence of CPPSs. CPPSs envision production systems with self-X abilities in response to external environmental changes, where X is a placeholder for one or more desirable abilities of a system subjected to a variable operation condition, such as self-adjustment, self-configuration and self-optimization. Therefore, CPPS is a topic worth studying. To have a holistic perspective of CPPSs, we formulated the following research question:

- **RQ 1.1:** What is the current research status of CPPSs?

We searched the review articles of CPPSs. Existing literature reviews of CPPSs either focus on a specific research topic, or general topics including the concept, characteristics, expectations, challenges and case studies of CPPSs. However, CPPSs research is scattered and needs to be structured for understanding their maturity. This led us to identify the following research gap:

- **Research gap 1.1:** The lack of a systematic literature review of CPPSs that investigates the development status of CPPSs according to their engineering life cycle.

In order to address this research gap, we proposed the following contribution in Section 2.1 of Chapter 2:

- **Contribution 1.1:** A systematic literature review of CPPSs on their concept and engineering development stages was performed, in order to have a global view on the current research status of CPPSs. Then, according to this literature review, a research map summarizing the main research activities of CPPSs in literature was proposed, which can help researchers to examine the maturity of the development status of CPPSs. Finally, a research agenda with several future research issues is proposed.

Among those future research issues, the transformation of legacy systems into CPPSs is our interest because it can bring enormous benefits to production systems in many aspects, such as technical, economic, and social aspects. In order to know the current research status on the transformation methods, we formulated the following research question:

- **RQ1.2:** What is the current research status of the transformation methods of legacy systems into CPPSs?

We searched review articles on the transformation methods. However, this is an emerging topic and there is no relevant literature review. This led us to identify the following research gap:

- **Research gap 1.2:** The lack of a literature review on the transformation methods of legacy systems into CPPSs.

In order to address this research gap, we proposed the following contribution in Section 2.2 of Chapter 2:

- **Contribution 1.2:** A literature review of methods for transforming legacy systems into CPPSs was performed.

Through this literature review, it has been concluded that existing methods either focus on the transformation of a specific components or give guidelines for transformation at a high level without specific methods and tools. Therefore, the following research gaps are identified:

- **Research gap 2:** The lack of a meta-model of CPPSs defining the essential elements of CPPSs and their relations, especially the elements of EISs.
- **Research gap 3:** The lack of a method indicating the elements to be transformed and their transformation sequence.
- **Research gap 4:** Lack of an evaluation of this transformation solution before its development and lack of the complementary combination of quantitative analysis based on standardized KPIs and qualitative analysis that considers various dimensions.

In order to address these research gaps, we formulated the following research questions:

- **RQ2:** Which elements need to be considered for the transformation towards CPPSs?
- **RQ3:** How to identify the elements that need to be added and modified in legacy systems for being CPPSs and what is the transformation sequence for these elements?
- **RQ4:** How to evaluate the benefits of the transformation solution?

To answer these research questions, the following contributions were proposed as follows:

- **Contribution 2:** To answer RQ2, a meta-model of CPPSs was proposed in Chapter 3, which serves as a foundation of the method to transform legacy systems into CPPSs. To the best of our knowledge, we confirm that the meta-model of CPPSs is complete. Although some related studies exhibit different elements of CPPSs, they are either more fine-grained or more abstract than our object classes or merely part of our defined object classes, so they still fall within the scope of the meta-model.
- **Contribution 3:** To answer RQ3 and RQ4, a method for transforming existing production systems with its integrated EISs into CPPSs was proposed in Chapter 4, which provided

a detailed process to guide people in visualizing which elements need to be added and modified and to help the manufacturer to determine whether to develop this transformation solution by weighing the expected benefits against the actual obstacles. Finally, to illustrate the usefulness and applicability of the proposed method, two case studies were introduced.

6.2 Limitations and possible solutions

Limitations related to our contributions and some possible solutions are illustrated as follows:

(1) On the systematic literature review of CPPSs

- Limitation: On the one hand, papers were only collected from the multidisciplinary database ISI Web of Science. On the other hand, because the search criteria were restricted to conference and journal articles, research published in other sources (e.g., books or reports) was excluded.
- Solution: More databases and published sources could be taken into account in future work to ensure its comprehensiveness.

(2) On the meta-model of CPPSs

- Limitation: We strive to develop a complete meta-model for CPPSs, but as technology develops, we cannot exclude the possibility of further model extensions.
- Solution: Since the proposed meta-model is extensible, new object classes can be added at any time as new technologies arise in CPPSs.

(3) On the transformation method

- Limitation: the transformation towards CPPSs is a very broad topic and includes overwhelming and complex tasks which are not instantaneous and cannot be simply handled by this thesis. When applying the system engineering principles to CPPSs, a generic transformation process towards CPPSs can be considered as a stepwise process that consists of three stages: concept development, engineering development and post development. For each stage, there are several phases, as shown in Figure 2.2. While the ultimate goal is to develop a comprehensive methodology for transforming legacy systems into CPPSs, at the moment this thesis is a preliminary study limited at the concept development stage. In the proposed method, the identification of elements that need to be added and modified relies only on the knowledge and experience of humans. In addition, the evaluation has only considered the technological, informational and organizational dimensions so far. However, manufacturers have to evaluate many other aspects.

- Solution: For identifying the elements that need to be added and modified, the experience collected from experts can be stored in a library for reuse in future projects and dedicated tools can be developed for automatic identification based on the experience. For evaluating more aspects of the benefits of the transformation solution, an evaluation of the economic aspect could be made by performing the cost-benefit analysis.

(4) On the case study

- Limitation: The proposed method is currently only applied in simulation-based and laboratory cases, but not in actual industrial cases. Though, the simulation-based and lab cases are to be understood as a step that shows the basic potentials of the method and provides a starting point for further test activities in real factory.
- Solution: Future work can apply the method in real industrial cases and try to achieve the Level V (Configuration Level) of the 5C architecture where all the advantages of CPPSs could be exploited.

6.3 Perspective

Future work will be devoted to the further extension of the method for transforming an existing production system with its integrated EISs into a CPPS. Since the method proposed in this thesis is currently positioned at the concept development stage, future works need to advance from the concept development stage to the engineering development stage. More specifically, we currently just identify the elements that need to be added and modified. The next step needs to address the detailed definition of the selected solution. It is initiated with a detailed design of the target system and the definition of the components, such as the connection of communication devices to a network, data flows and their relations, and input/output signals. It can be seen that this step still includes many aspects and our research perspective focuses on the transformation of decision-making processes in CPPSs.

In the proposed meta-model of CPPSs, decision-making is an important aspect of organizational relationships. The organizational relationships involving decisions are listed in Table 6.1. They can be interpreted as a number of questions from which some features to be considered in the decision-making process can be extracted.

Table 6.1 Organizational relationships related to decision making

Organizational relationships	Interpretations	Decision-making features
Decision Center & Decision	How decisions are made?	• Decision-making structure • Drivers for decision-making • Models or tools that support decision-making
	Which decisions are made?	• Decision-making levels
Decision Center & (Product, Machine, Human, EIS Software Package)	In which decision centers?	• Decision centers
	What is the role of humans in decision-making?	• Role of humans in decision-making
	Which person profiles are required for decision-making?	• Person profile required for decision-making

We investigate how these decision-making features change in the transformation from legacy systems to CPPSs, as shown in Table 6.2.

Table 6.2 Transformation of decision-making features

Decision-making features	Legacy production systems	CPPSs
Decision-making structure	Centralized and highly hierarchical structure based on ISA 95	Structure consists of ERP and CPPSs
Drivers for decision-making	Event-driven	Data-driven
Models or tools that support decision-making	Deterministic model, stochastic model, forecasting and statistical models, other models (MCDM, AHP, etc.), AI techniques	Evolving AI techniques: ML and DL
Decision-making levels	Operational, tactical and strategical level	(Near) real-time, operational, tactical and strategical level
Decision centers	Human, EISs	Human, EISs, CPPSs components
Role of humans in decision-making	Make decisions at all decision planning levels	Make decisions only at high levels
Person profiles required for decision-making	Troubleshooting, analytical skills, problem-solving skill, leadership.	Increased cognitive skills and social skills

The detailed explanation of the transformation of these decision-making features is as follows:

- Decision-making structure

In the legacy system, the decision-making structure is based on the ISA 95 standard. On the uppermost level, ERP define organization related decisions on time frames of years, months, weeks, and days. Then MES define production processes related decisions on time frames of days, hours, minutes and seconds. Finally, the bottom three levels define the actual production processes and their automated control activities, which typically operate on time frames of minutes, seconds and faster. In this hierarchical structure, each level interacts only with its adjacent levels.

CPPSs change this hierarchical decision-making structure. As shown in Figure 6.1, the decision-making will be managed by two large systems: ERP and CPPSs (Rossit et al., 2019a), which means that the bottom four levels of ISA 95 are incorporated into CPPSs. This is due to the ability of CPPSs to carry out a wide spectrum of activities, ranging from level 0 to level 3. The decisions about the goals to be pursued will still be handled by the ERP, while all other decisions will be automatically run by CPPSs. However, this means that current MES, which take care of dispatching work orders and their scheduling, are absorbed by CPPSs. This change has raised a dispute on the role of MES in CPPSs, specifically with respect to the functions they support in CPPSs. To shed light on the role of MES in CPPSs, we published a conference article (X. Wu et al., 2020a), which was entitled "Functional analysis of Manufacturing Execution Systems (MES) in Cyber Physical Production Systems (CPPSs)" in the 13th conference of modeling, optimization and simulation (MOSIM 2020). The main results of this article are summarized in Appendix B.

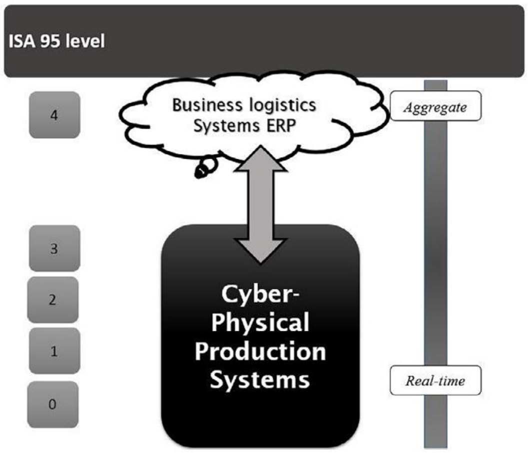

Figure 6.1 Decision-making structure managed by ERP and CPPSs (Rossit et al., 2019a).

- Drivers for decision-making

In the legacy system, decision-making is event-driven, which assumes that decisions are made after facing unexpected events, like dynamic scheduling (Katragjini et al., 2013).

However, CPPSs allow the availability of big data to anticipate events, so decisions can be made ahead of time, which enables the data-driven decision-making. The adoption of data-driven decision-making starts to be one of the key competitive advantages of the enterprise in the new dynamic nurture of the market (Ahmed et al., 2021). Some data-driven decision-making methods are proposed, as in (Rossit et al., 2019b), (Romeo et al., 2020) (Chouliaras & Sotiriadis, 2020).

- Models or tools that support decision-making

Decision-making considers different alternatives and selects the best ones among various choices (Hoffmann Souza et al., 2020). As decision-making usually involves several options, models or tools are used in the search for the best results, from simple information reporting tools to sophisticated AI systems.

In the legacy system, many models are developed, including deterministic model (linear programming, network model, etc.), stochastic model (Markov process model, simulation model, decision trees/game theory, etc.), forecasting and statistical models, other models (MCDM Models, AHP, Visual interactive modeling, etc.) and AI (neural networks, rule-based, knowledge-based, case-based reasoning, genetic algorithm, and fuzzy logic systems) (E. B. Kim & Eom, 2016).

In CPPSs, the evolving of AI, especially ML and DL, presents an important and remarkable paradigm shift for decision support because it enables to make timely decisions with minimal human involvement and improve the decision-making process in presence of disruptions, as presented in (Arinez et al., 2020; Gupta et al., 2021; J. Lee et al., 2020).

- Decision-making levels

In the legacy system, according to the importance of the decisions and the length of the planning horizon, decisions are categorized into three levels: strategic decisions (long-term of several years), tactical decisions (mid-terms between a few months and one year), and operational decisions (short-term between a few days and a few weeks) (Anthony, 1965; Pereira et al., 2020).

In CPPSs, a new time horizon, (near) real-time decisions, emerges, thanks to the availability at any time of massive data and efficient data processing technologies. Because of the emergence of this new horizon, CPPSs could change the original planning horizon. Existing studies in the literature mainly focus on the transformation of the decision planning horizon from the operational level to the (near) real-time level. In specific, decisions about resource allocation and scheduling traditionally made in MES at the operational level could be made by smart components of CPPSs at the (near) real-time level, as presented in (Kocsi et al., 2020).

- Decision centers

In the legacy system, most of the decisions were made centrally in EISs. However, in CPPSs, decisions related to lower scopes of operations can be decentralized to intelligent components of CPPSs (such as machines and products), so that faster decisions can be made automatically. Some examples are as follows, as presented in (Ding et al., 2019) and (Villalonga et al., 2021).

- Role of humans in decision-making

In the legacy system, humans make most of the decisions. However, in CPPSs, more and more decisions will be made by CPPSs automatically, while humans are increasingly excluded from simple and repetitive decisions and only focus on high level decision-making, such as defining the goals and guidelines for the company (Rossit et al., 2019a).

- Person profile required for decision-making

In the legacy system, many of the activities must be performed by humans, so many human skills are required for decision-making, such as troubleshooting, analytical skill, problem-solving skill and leadership. In CPPSs, there are more complex and difficult tasks to perform, so a number of different actors across departments need to interact together. Therefore, humans need to be equipped with increased cognitive skills (problem analysis, learning, knowledge building, etc.) and social skills (participation, communication, cooperation, etc.) (Schuh et al., 2020).

According to the above analysis on these decision-making features, we then envisage some future research directions as follows.

- The transformation of the decision-making structure enables CPPSs to have access to more data than before, bypassing the adjacency constraints inherent. Therefore, how to treat and exploit these data would always be one of the primary challenges. Although AI techniques are increasingly developed, their successes are currently mainly focused on prognostics, maintenance, process monitoring and optimization at the component level. Future work on applying AI could be extended to system-level decision-making, such as which strategies to follow, which products to produce and which markets to target.
- In the future, there should have more kinds of high-level decisions in legacy systems that change their planning horizons to lower levels. Therefore, which kinds of decisions will change their decision-planning levels could be a future research focus.
- Although decentralized decisions made by CPPSs components increase the responsiveness of the entire system, they also have limitations when they are not properly coordinated to consider what is the best for the enterprise or when they require additional management input to align them with the enterprise’s overall goals.

Therefore, certain decisions must be taken centrally, for instance, decisions concerning the company's strategy. This raises a future research topic about how to develop the capability to manage decision rights in a way that strikes the right balance between centralization and decentralization in order to maximize the effectiveness and efficiency of decision-making processes.

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Appendices

The appendices section contains:

- Appendix A - includes meanings of supporting data according to the International Standard ISO 22400-2 (2014).
- Appendix B – includes the main results of our published article (X. Wu et al., 2020a).

Appendix A Meanings of supporting data

- *Planned operation time (POT)*: The scheduled time during which a work unit can be utilized.
- *Planned busy time (PBT)*: The planned time during which a work unit is busy.
- *Planned down time (PDOT)*: The planned time during which a work unit is unable to produce, which may include scheduled breaks, meetings, maintenance, etc.
- *Actual unit busy time (AUBT)*: The actual time that a work unit is used for the execution of a production order.
- *Actual unit down time (ADOT)*: The actual time when a work unit is not executing a production order even if it is available.
- *Actual order execution time (AOET)*: The time from the start of an order to its completion on a work unit.
- *Actual transportation time (ATT)*: The actual time for transporting parts on or between work units, such as loading and unloading time.
- *Actual queueing time (AQT)*: The actual time during which the part is waiting to go through a manufacturing process, i.e., queueing time in a buffer.
- *Actual unit delay time (ADET)*: The actual time in which the production process is delayed due to malfunction-caused interruptions, minor stoppages, and other unplanned events.
- *Actual unit processing time (AUPT)*: The time necessary for production and setup on a work unit for an order.
- *Actual unit setup time (AUST)*: The time used for the setup.
- *Actual production time (APT)*: The actual time in which a work unit is producing a production order, which only includes the value-adding functions.
- *Actual personnel attendance time (APAT)*: The actual time that an operator is available to work on production orders.
- *Actual personnel work time (APWT)*: The time that an operator actually executes an order.
- *Good quantity (GQ)*: The produced quantity that meets quality requirements.
- *Scrap quantity (SQ)*: The produced quantity that does not meet quality requirements and has to be scrapped or recycled.
- *Rework quantity (RQ)*: The quantity that fails to meet the quality requirements, but these requirements can be met by reprocessing.

- *Produced quantity (PQ)*: The quantity that a work unit has processed (which may include the reworked ones and scraped ones) in relation to a production order.

Appendix B - Function analysis of MES in CPPSs

Research context and problems

Traditionally, the MES was positioned as a middle layer to bridge the shop floor with the ERP system. The emergence of CPPSs transforms the automation pyramid into a decentralized structure (Monostori et al. 2016). This transformation leads to a vague on the role of MES in CPPSs: Does this decentralized structure of CPPSs make MES superfluous? If not, what is the role of MES in CPPSs? And how does MES need to change to fulfill this role?

Research objectives and methods

In current academic research, answers ranging from "no role because the hierarchical structure will be dissolved" and "fewer and fewer role because MES functions will be cannibalized by enhanced CPPSs and ERP functions" right up to "central role because MES will be the decision-making center of an organization and create the optimal value chain". The existing studies are either based on literature reviews or empirical methods, but no one builds functional models to elaborate and compare the functions between CPPSs and MES. Therefore, this paper aims to shed light on the role of MES in CPPSs, by proposing functional models of CPPSs and MES and thus comparing their functions.

Firstly, functional models of CPPSs and MES are proposed in the form of IDEF0 diagrams. Then, data flows between the functional models of CPPSs and MES are described and the functions of the two are compared.

Research results and conclusion

MES functions are still required for CPPSs, but they need to be presented in new and different forms. Firstly, future MES can be used as a digital twin due to its ability to collect data across all the areas of MOM (including production, quality, inventory and maintenance), provide digital images and monitor manufacturing processes in real-time. Secondly, some functions will be incorporated into the CPPSs' functions. For example, the MES's function "detailed schedule" will only have high-level tasks, i.e., making rough planning of manufacturing orders, while flexible planning of partial orders will be made by local elements of CPPSs. Thirdly, in Industry 4.0 context, the function of performance analysis in MES becomes more complex and important. With the development of ICT, the amount of data collected from the shop floor increases tremendously. MES should always be required to present the most relevant data to humans for decision-making. In addition, MES software will move from monolithic software systems towards functional modules that will be implemented in a highly distributed way. Therefore, the next-generation MES require greater flexibility, dynamism and improved functionality than today's MES.

Xuan WU

Transformation des systèmes de production existants et leur systèmes d'information d'entreprise (EISs) en systèmes de production cyber-physiques (CPPSs) dans le contexte de l'industrie 4.0

Résumé

Les systèmes de production cyber-physiques (CPPSs en anglais), qui se caractérisent par une interaction étroite entre les mondes cyber et physiques, sont la pierre angulaire de l'industrie 4.0. Ils apportent, dans un environnement changeant, intelligence et agilité aux entreprises manufacturières. Cependant, leur mise en œuvre réelle se heurte aux systèmes patrimoniaux existants au sein des ateliers et qu'il s'agit de faire évoluer. La thèse vise donc à proposer une méthode guidant la transformation d'un système existant de production intégré avec son système d'information d'entreprise (EISs) en un CPPS. Afin d'avoir une compréhension des éléments qui doivent être considérés au cours de cette transformation, un méta-modèle de CPPS est proposé. Il définit les éléments essentiels à prendre en compte et leurs relations. Sur la base de ce méta-modèle, une méthode de transformation est proposée. D'une part, elle guide la définition des éléments à ajouter et/ou à modifier au sein du système de production existant . D'autre part, elle permet l'évaluation qualitative et quantitative du CPPS potentiel. Pour illustrer l'applicabilité générale et l'intérêt de cette méthode, des cas de simulation et de laboratoire sont présentés.

Mots clés: Systèmes de production cyber-physiques, Systèmes d'information d'entreprise, Transformation entreprise, Développement méta-modèle, Industrie 4.0

Résumé en anglais

Cyber-Physical Production Systems (CPPSs), which are characterized by a tight interaction of computational and physical elements, enable the manufacturing industry with intelligence, agility and innovation in response to changeable market requirements in the context of Industry 4.0. However, the real-scale implementation of CPPSs in industrial practices is still in its infancy due to the legacy barrier. The thesis, hence, aims at proposing a method to transform an existing production system with its integrated Enterprise Information System (EISs) into a CPPS. To have a common understanding of the elements that need to be considered for this transformation, a meta-model of CPPSs that defines all essential elements and relationships between these elements is proposed. Based on the meta-model of CPPSs, a method, which provides a detailed process to guide people in visualizing which elements need to be added and modified and to help manufacturers to determine whether to develop this transformation solution by an evaluation of its benefits, is proposed. To demonstrate the efficacy and general applicability of this method, simulation and laboratory cases are introduced, which pave the way for further testing within real systems in future work.

Keywords: Cyber physical production systems (CPPSs), Enterprise information systems (EISs), Enterprise transformation, Meta-model development, Industry 4.0