Cadre méthodologique pour la conception et modélisation des systèmes de production - Intégration des exigences sécurité des opérateurs

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THÈSE

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Cadre méthodologique pour la conception et modélisation des systèmes de production – Vers une intégration des exigences sécurité des opérateurs

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AC	Automatic characterization
AD	Axiomatic design
AFNOR	Association française de normalisation
ATF	Automatic technical function
BES	Behavior-Energy-Structure
BF	Basic function
C2C	Cradle to cradle
CA	Criticality Analysis
CAD	Computer aided design
CPM	Characteristics-Properties modelling
CS	Components selection
CSA	Current system analysis
CTOC	Converter, transmitter, operator, and control)
DFSS	Design for six-sigma
DfX	Design for X
DMAIC	Define, Measure, Analyze, Improve, Control
DP	Design parameter
EC	Energetic Characterization
ESA	Expected system analysis
ETA	Event tree analysis
ETF	Energetic technical function
EZID	Energy Analysis for Systematic Hazard Identification
FA	Functional analysis
FBS	Function-Behavior-Structure
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects, and Criticality Analysis
FR	Functional requirement
FTA	Fault tree analysis
GFBS	Goal-Function-Behavior-Structure
IPPD	Integrated Product and Process Design
IRAD	Innovative Risk Assessment Design
KPI	Key performance indicator
MOSTRA	Modèle de Situation de travail

MSDD	Manufacturing System Design Decomposition
NER	New and emerging risk
OSA	Operating system analysis
PAG	Performance Analysis Agent
PDD	Property-Driven Development
QFD	Quality function deployment
ROI	Return on investment
SA	Systematic approach
SI	Safety indicator
SMED	Single-minute exchange of die
TRIZ	Theory of inventive problem solving
VI	Volume of influence

Résume étendu en français

1. Introduction

1.1 Définition de la problématique et question scientifique

De nouveaux processus, systèmes et machines sont en cours de développement pour améliorer le taux de production et la réactivité des processus de fabrication. Ces contributions doivent être alignées avec les performances requises du système et les conditions industrielles fluctuantes. Le marché a une influence considérable sur le développement des produits [Aksoy 2017]. Dans l'équilibre en constante évolution entre l'offre et la demande, les industries doivent adapter leurs produits aux besoins des clients de manière innovante et efficace pour séduire davantage de clients et augmenter les bénéfices. De ce point de vue, l'équipe de conception a une tâche complexe entre les mains car le système de production doit répondre aux exigences techniques ainsi qu'aux exigences du marché et de la sécurité.

Parallèlement, depuis de nombreuses années, l'utilisation des machines dans l'industrie est réglementée pour répondre aux normes de sécurité et protéger les utilisateurs. Il existe autant de mesures de sécurité que de mesures ergonomiques visant à protéger les travailleurs à court et à long terme. Trop d'accidents du travail et de problèmes ergonomiques sont observés sur les postes de travail. En effet, en France en 2019, d'après les données collectées par la Sécurité sociale, le nombre d'accidents du travail a augmenté de 0,6% par rapport à 2018 (655715 sinistres reconnus en 2019 après une augmentation de 2,9% en 2018). De même, le nombre de maladies professionnelles a augmenté de 1,7% pour la deuxième année consécutive par rapport à 2018, avec 50392 cas reconnus. Cette augmentation des accidents et maladies liés au travail dans les environnements industriels appelle à la prise en compte des risques de sécurité lors de la conception de tout système impliquant des travailleurs humains.

Sur la base du constat discuté dans la section précédente, et compte tenu de l'hétérogénéité et, la plupart du temps, de la non-compatibilité des pratiques industrielles, l'objectif est de présenter un cadre de conception multicritère pour concevoir des systèmes de production complexes et multi-technologiques afin de répondre aux exigences de conception, et suffisamment flexible pour intégrer des indicateurs clés de performance (KPI) tels que la sécurité humaine. Dans ce travail, les exigences de sécurité sont utilisées comme critères de décision pour illustrer l'intégration dans le processus de conception. La question suivante résume l'objectif de ce travail de recherche :

Comment concevoir un système de production intégrant la sécurité des opérateurs tout en respectant tous les objectifs de conception en termes de temps, de coût et de performance ?

Afin de répondre à cette question, trois problématiques scientifiques ont été définies :

- Question 1 : Comment définir un cadre de conception pour gérer de manière cohérente le processus de conception, la modélisation du système et le raisonnement de conception ?

- Question 2 : Comment définir une méthodologie d'analyse des risques liés à la sécurité des travailleurs du système de production ?

- Problématique 3 : Comment établir une connexion entre les données de conception et les outils d'analyse des risques pour prendre en compte la sécurité des opérateurs le plus tôt possible dans la conception des systèmes de production ?

1.2 Approches et outils

Afin de répondre aux exigences industrielles lors de la conception, il est essentiel de gérer de multiples éléments : les représentations du produit, l'organisation du projet, les connaissances techniques et les ressources disponibles. Sur la base de ces éléments, cette étude a choisi d'adopter une perspective d'analyse triaxiale directement liée aux différentes théories et approches de la conception présentes dans la littérature. Ces théories seront classées en termes de raisonnement sur le projet, le produit et la conception.

Dans la littérature, la plupart des approches cherchent à fournir aux concepteurs des outils méthodologiques applicables à des cas généraux de conception de produits basés sur différents points de vue du processus de conception. Certains auteurs proposent des approches centrées sur le projet en donnant des étapes structurées, organisées et séquentielles à suivre par le concepteur. Dans ces approches, l'équipe de conception est au centre du projet, et la tâche consiste à définir ce qu'il faut faire mais en suivant toujours les mêmes étapes séquentielles [Pahl et al. 2007] [Bonjour et al. 2003]. La performance du résultat final est évaluée en fonction de l'efficacité du projet ; si le processus a été rigoureusement suivi, la solution finale devrait répondre aux besoins initiaux.

D'autres auteurs proposent des approches de conception qui définissent le processus de conception autour du modèle de produit. Ces méthodes se concentrent sur le cycle de vie du produit et son interaction avec l'environnement [Suh 2001] [Gero & Kannengiesser 2004]. Cependant, la structure du processus n'est pas aussi bien développée que dans d'autres approches. La performance du produit final est évaluée exclusivement à partir de l'efficacité de la solution à répondre aux besoins du client ; c'est-à-dire que si le concepteur a pu extraire les informations correctes sur ses fonctions principales et son comportement, le produit devrait être, en théorie, capable d'accomplir sa mission. Ici, le rôle du concepteur dans la définition de l'objectif est crucial car c'est à partir de ces informations que le produit sera conçu.

Le troisième groupe d'approches de conception repose sur les activités du concepteur, où des étapes consécutives de synthèse et d'analyse sont appliquées pour converger vers les caractéristiques et les propriétés du produit final [Weber 2009]. Ces approches décrivent mieux le rôle du concepteur et considèrent certains aspects du point de vue du produit. De même, les approches mixtes reprennent certains éléments des autres et les intègrent pour offrir un processus complet de produit-projet [Antony & Coronado 2002].

Toutes les approches susmentionnées font référence à l'objet d'étude en tant que produit. Dans le cas de ce travail de recherche, l'objet d'étude est défini comme un système qui est considéré comme un ensemble de composants qui interagissent entre eux et remplissent des fonctions prédéterminées pour atteindre un objectif spécifique. Ces composants sont répartis dans différents sous-systèmes. D'autre part, un produit est considéré comme un composant unique conformé par des pièces individuelles.

En ce qui concerne l'intégration de la sécurité, de nombreux auteurs ont étudié la théorie de la conception pour l'enrichir d'autres aspects pertinents dans le contexte industriel. Les contributions des théories et outils de conception considérant la santé et la sécurité sont détaillées par [Sadeghi et al. 2016]. Cependant, il est pertinent de noter que ces méthodes et outils ne sont appliqués que dans des conditions spécifiques, et leur intégration dans le processus de conception est, la plupart du temps, limitée compte tenu des approches actuelles. La norme [EN ISO 12100 2010] fournit un diagramme représentant le processus de réduction des risques du point de vue du concepteur. La norme propose également une approche itérative du processus qui distingue plusieurs étapes nécessaires pour minimiser le risque résiduel. Ce processus peut être lourd à appliquer tel que décrit dans la norme car il est itératif et chronophage, et nécessite des compétences que les équipes de conception n'ont pas forcément.

1.3 Méthodologie de recherche

Comme cela a été exposé dans les sections précédentes, l'objectif de la thèse est de proposer une méthode de conception de systèmes de production qui prend en compte les exigences industrielles de la solution finale. En conséquence, la base de la thèse peut être identifiée dans la figure 1.1. La bulle de la science de la conception représente les trois principaux éléments de la conception de produits : le processus de conception, le modèle de produit et les activités de raisonnement de la conception.

Selon [Haik et al. 2015], le processus de conception est une procédure de prise de décision (souvent itérative), dans laquelle les sciences fondamentales, les mathématiques et les sciences de l'ingénieur sont appliquées pour convertir de manière optimale les ressources afin d'atteindre un objectif fixé. Concernant la modélisation du produit, [Geryville et al. 2007] déterminent que l'architecture du produit est définie non seulement par la décomposition du produit final en composants, fonctions ou comportements, mais aussi par les interactions entre tous les composants. [Do & Gross 1996] affirment que les activités de raisonnement de conception correspondent aux processus mentaux de résolution de problèmes des concepteurs tels que l'analyse, la synthèse et l'évaluation qui sont fondamentaux lors de tout problème de conception. Ces trois éléments interagissent et s'influencent mutuellement pour donner forme à la solution de conception. Les interactions entre le processus de conception et le modèle de produit peuvent être considérées comme bidirectionnelles dans le sens où la définition du produit détermine les différentes phases de conception du processus, mais en même temps, ces phases définissent ses caractéristiques. Les interactions entre le modèle de produit et les activités de raisonnement de conception ne sont pas directes car ces activités servent de lignes directrices nécessaires dans les phases de conception pour définir les caractéristiques du produit.

Sur la bulle des indicateurs clés de performance (KPI) apparaissent les différents indicateurs qui pourraient être intégrés dans la méthode de conception pour répondre aux exigences industrielles. Dans ce travail, la sécurité est l'indicateur à intégrer dans le processus pour valider la flexibilité et l'adaptabilité de la méthode de conception. La figure 1 apparaîtra dans différentes parties du manuscrit pour montrer les éléments développés dans les différents chapitres.

Compte tenu de tout ce qui précède, la méthodologie de recherche a été divisée en cinq parties :

Partie 1 : Aperçu des principaux concepts des théories et méthodes de conception, identification des risques et hypothèses de leur intégration.

Partie 2 : Développement d'un cadre général de conception de systèmes de production basé sur les résultats des projets de recherche précédents.

Partie 3 : Développement d'un outil d'analyse des risques basé sur des paramètres de sécurité compatibles avec le cadre général proposé et basé sur les éléments de sécurité retenus lors de la partie 1.

Partie 4 : Intégration de l'outil d'analyse de risque dans le cadre général de conception. Représentation explicite de leurs éléments communs et de leurs interactions.

Partie 5 : Application de la méthode de conception sur une étude de cas. Cette partie est présentée comme la dernière, mais elle a été développée en parallèle avec le développement des quatre autres parties.

Elle permet d'identifier et d'analyser les théories et les méthodes qui répondent partiellement ou entièrement à la question scientifique posée. L'état de l'art est défini comme le résultat de l'analyse de la description du cadre et de la méthodologie. La deuxième étape consiste à définir les éléments structurels de la méthode. Les idées principales de la thèse sont élaborées et démontrées dans cette étape. Cette étape est suivie par le développement de l'outil d'analyse des risques. Les détails du développement sont donnés ici. La quatrième partie présente l'intégration de l'identification des risques dans le processus de conception. Enfin, dans la cinquième partie, un exemple est donné pour valider chaque composante de la méthode.

1.4 Contributions attendues de la thèse

Cette section donne un aperçu des contributions générales attendues de la thèse. Les contributions détaillées sur les solutions spécifiques sont discutées dans les chapitres correspondants. Les contributions de la thèse peuvent être classées en trois catégories : les contributions liées à la structure générale du cadre de conception pour les systèmes de production, le modèle de produit basé sur l'énergie, et l'intégration des KPIs dans la conception industrielle indépendamment de la nature de l'indicateur.

La première contribution est un cadre méthodologique pour la conception de systèmes de production basé sur des concepts de l'ingénierie systématique et de l'ingénierie des systèmes avec l'intégration d'approches de sécurité des opérateurs et de fiabilité opérationnelle dès les phases d'élicitation des exigences. La structure proposée du cadre devrait contribuer à la communauté scientifique en fournissant un processus de conception qui permet la traçabilité de chaque décision prise en structurant le raisonnement mental du concepteur. La confrontation entre les approches de conception existantes et les conditions réelles de conception d'un système de production dans l'industrie met en évidence l'absence d'une approche plus détaillée, étape par étape, pour surmonter les obstacles potentiels qui pourraient apparaître au cours du processus. La méthode proposée définit ces étapes manquantes pour réussir le développement d'un projet de conception.

La deuxième contribution repose sur la proposition d'un modèle de produit basé sur les interactions et les traitements énergétiques qui se produisent à l'intérieur d'un système de production. Cette approche identifie les éléments critiques pour passer de l'architecture fonctionnelle à l'architecture organique du système, ce qui s'est avéré être l'une des étapes les plus problématiques du processus de conception. On s'attend à ce que le modèle de produit soit suffisamment flexible pour être appliqué dans de grands systèmes de production et pour supporter différentes analyses de scénarios.

Par la suite, la dernière contribution est soutenue par l'intégration des deux précédentes. L'intégration d'un indicateur de performance clé dans le cadre de conception proposé se fait grâce à la flexibilité du modèle de produit basé sur l'énergie. Pour ce travail, les indicateurs de sécurité ont été utilisés comme approche primaire en raison du développement de nouvelles méthodes industrielles qui pourraient affecter la sécurité humaine. Cependant, ce n'est qu'une des nombreuses approches qui peuvent être incluses et adaptées au cadre de conception, comme la durabilité ou la productivité. D'autres projets de recherche ont exploré l'intégration d'indicateurs spécifiques dans la conception, mais pas d'une manière générique où l'approche peut être échangée sans modifier le cadre général. Cette interchangeabilité donne au cadre de conception la possibilité d'être adapté et de répondre aux besoins du client sans changements significatifs.

2. Revue de la littérature

2.1 Conception et sécurité

En termes de théories et de méthodes de conception, de nombreuses approches ont été proposées pour les produits généraux. Cependant, il est essentiel de noter que même si elles sont généralement utilisées pour des produits individuels, il est également possible de les appliquer à la conception de systèmes. Comme expliqué dans le chapitre 1, Dans ce projet de recherche, l'objectif principal est la conception de systèmes de production, il est donc important de faire la différence avec les objets d'étude utilisés dans la littérature (produits). L'utilisation du système comme objet d'étude implique la prise en compte d'aspects organisationnels et de cycle de vie différents de ceux considérés pour un seul produit, tels que les changements de calendrier de production ou la phase d'installation. Le niveau de détail considéré pour un système varie considérablement par rapport à celui d'un produit unique. Dans un système, le produit peut être considéré comme l'un des composants de base du système qui remplit une fonction donnée sans tenir compte de ses parties individuelles.

Comme mentionné dans le chapitre précédent, les facteurs humains sont étroitement liés aux performances d'un système de production. La façon dont les travailleurs se comportent dans un système de production a un impact sur les paramètres de production et l'apparition de situations dangereuses. Le concept de situation de travail est défini comme l'ensemble de tous les composants du système de production et des travailleurs humains effectuant une ou plusieurs tâches par le biais d'interactions pour atteindre un objectif prédéfini dans des conditions de travail prédéfinies [Hasan et al. 2003]. Un risque existe lorsqu'un travailleur est exposé à un ou plusieurs phénomènes susceptibles de causer des dommages dans cette situation de travail. C'est l'une des principales raisons pour lesquelles les informations relatives à la situation de travail doivent être prises en compte lors du processus de conception.

En parlant de la tâche de conception, il est possible de dire qu'un projet de conception est composé d'une dimension structurelle sous la forme d'un cadre, d'une dimension organisationnelle sous la forme d'un calendrier de développement, d'une dimension morphologique sous la forme d'un modèle de système pour le développement de la solution finale, et d'une dimension analytique sous la forme d'activités de résolution de problèmes. Comme le montre la figure 2.1, d'un point de vue général, ces éléments sont la planification du projet qui est déterminée par le processus de conception en tant qu'ensemble de phases organisées, le modèle de produit, qui enregistre l'évolution de la conception du produit depuis les besoins du client jusqu'à la solution finale, et les activités de raisonnement de la conception qui influencent les actions à entreprendre pour atteindre les objectifs intermédiaires de la conception.

2.2 Approches du processus de conception

Les méthodologies basées sur le processus de planification et de conception du projet fournissent au concepteur des étapes organisées, structurées et séquentielles (figure 2.4). C'est le cas de la conception systématique proposée par [Pahl & Beitz 1996, Pahl et al. 2007], qui décrit la conception technique comme une séquence de quatre phases : La définition du cahier des charges, la conception architecturale, la conception de réalisation et la conception détaillé. Chacune de ces quatre phases comprend une séquence d'activités réalisées de manière itérative [Tate & Nordlund 1996, Unger & Eppinger 2011]. Un autre exemple de ce groupe est l'ingénierie des systèmes [Bonjour et al. 2003, De Weck et al. 2011], qui se définit comme un processus d'intégration de toutes les disciplines impliquées dans le cycle de vie d'un système en tenant compte des différents besoins afin de développer une solution économique, efficace et satisfaisante à tous points de vue. [Menand 2008, Messaadia 2008].

2.3 Processus de conception et modélisation du produit

Les approches basées sur la modélisation du produit proposent de représenter les fonctions et le comportement du produit de conception (Figure 2.9). Parmi celles-ci, le cadre Function-Behavior-Structure (FBS) proposé par [Gero 1990, Gero & Kannengiesser 2004], caractérise la structure du produit en utilisant ses fonctions à travers son comportement. Le cadre FBS a révélé certaines ambiguïtés, notamment l'absence d'une description cohérente des fonctions [Vermaas 2007]. Une autre théorie qui fait partie de ce deuxième groupe est la conception axiomatique, proposée par [Suh 1990, 2001], qui représente le produit dans quatre domaines différents : client, fonctionnel, physique et processus. Le processus de conception fait des allers-retours entre les quatre domaines et utilise deux axiomes pour valider les choix de conception : l'axiome d'indépendance et l'axiome d'information. [Albano 1994].

2.4 Approches de modélisation des produits et des fonctions

Dans cette section, certaines approches de modélisation de produits et de fonctions sont expliquées afin d'identifier les principaux éléments nécessaires à l'intégration du modèle de produit dans le cadre de conception. Selon [Brissaud & Tichkiewitch 2001], l'organisation de boucles de rétroaction continues entre les utilisateurs du produit et les concepteurs et fabricants peut contribuer à améliorer la conception du produit. De nombreux auteurs ont tenté d'établir des approches d'aide à la conception évolutive basées sur la connaissance des caractéristiques réelles de l'environnement de travail du produit [Goncharenko et al. 1999]. Ces méthodes sont principalement utilisées pour la planification et l'analyse de la maintenance.

Elles prennent en compte l'engagement réciproque des opérations de conception et de maintenance, ainsi que les méthodes et les avantages possibles de la circulation et de l'utilisation des informations sur le produit [Goncharenko & Kryssanov 1999]. Des idées de surveillance et de diagnostic des défauts ont été définies [Van Houten et al. 1998]. La surveillance est le processus de comparaison du comportement réel d'un produit avec le comportement anticipé par un modèle (Figure 2.13).

2.5 Approches de raisonnement de la conception

L'interaction entre les phases de conception et les activités de raisonnement de conception est unidirectionnelle, ce qui signifie que le processus de conception affecte directement ces activités. C'est pourquoi certaines autres approches s'appuient sur le raisonnement du concepteur, où des étapes successives de synthèse et d'analyse sont réalisées pour définir les propriétés et caractéristiques du produit fini (Figure 2.15). Par exemple, la modélisation des caractéristiques et propriétés (CPM) proposée par [Weber et al. 2003 ; Weber 2005, 2009] est basée sur la distinction des caractéristiques et propriétés d'un produit. Elle offre un cadre général, tel qu'exprimé par [Köhler et al. 2008], pour d'autres théories de conception, notamment [Hubka & Eder 1987]. Dans ce groupe, on considère également la conception pour Six-Sigma (DFSS) [Antony & Coronado 2002 ; De Feo & Bar-El 2002], une méthodologie conçue pour améliorer le pré-développement de nouveaux produits et services, en fournissant une manière systématique de gérer les produits et les ressources et en donnant une perspective pragmatique du processus de conception [Treichler et al. 2002].

2.6 Intégration de la sécurité dans la conception

En ce qui concerne l'intégration des facteurs humains dans le processus de conception, la revue de la littérature a mis en évidence trois approches principales : premièrement, les outils d'évaluation de la sécurité pour évaluer les situations de travail [Chinniah et al. 2017 ; Fadier & Ciccotelli 1998 ; Houssin et al. 2006 ; Houssin & Coulibaly 2011]. Comme le montre la figure 2.18, ces outils d'évaluation de la sécurité sont directement appliqués au processus de conception, sur une ou plusieurs étapes. Certains chercheurs considèrent que les outils traditionnels d'analyse de la sécurité pendant le processus de conception sont suffisants pour identifier les situations dangereuses [Harms-Ringdahl 1987 ; Gauthier & Charron 2002]. D'autres utilisent des outils virtuels pour traiter les mêmes risques de sécurité [Dukic et al. 2007]. Pour [Ericson 2015], l'analyse de sécurité peut être qualitative, semi-quantitative ou quantitative. Pour [De Galvez 2017], l'identification des risques peut être réduite au flux d'énergie à l'intérieur d'un système.

Deuxièmement, la conception pour la sécurité inclut les exigences de sécurité comme une propriété intrinsèque du système [Wang 1997 ; Rasmussen 1994]. Comme le montre la figure 2.19, des modèles de système et des étapes de conception spécifiques sont proposés pour répondre aux exigences de sécurité. Dans la littérature, certains travaux de recherche ont appliqué des théories et des méthodes de conception pour améliorer la sécurité des systèmes de production. C'est par exemple le cas de [Van Duijne et al. 2007] et [Fadier & De la Garza 2006].

Troisièmement, les méthodologies de conception et les outils d'évaluation de la sécurité qui sont développés ou adaptés pour travailler simultanément font partie du même processus de conception mais ne sont pas uniquement axés sur les paramètres de sécurité, et la détection des risques tels que IRAD et la conception pour la sécurité appliquée au FBS [Slatter et al. 1989 ; Sadeghi et al. 2017] ou la conception axiomatique en ergonomie [Helander & Lin 2002]. Certains de ces travaux proposent d'utiliser le flux énergétique pour évaluer le niveau de risque d'un système de production, la modélisation du système doit donc être basée sur le flux énergétique. Comme le montre la figure 2.20, ces approches proposent des variantes de certaines des théories et méthodes de conception largement utilisées dans la littérature, telles que la théorie Fonction-Comportement-Structure [Gero & Kannengiesser 2004] et l'ingénierie systématique [Palh et al. 2007].

La variété des sujets et le nombre de recherches liées à l'amélioration de la sécurité pendant le processus de conception font qu'il est difficile pour les chercheurs d'avoir une vue d'ensemble complète du domaine. [Sadeghi et al. 2016] ont classé ces approches en deux groupes de recherche principaux et ont fourni les éléments à prendre en compte dans le cas de la conception pour la sécurité (figure 2.21). Suite aux discussions sur les sujets de recherche d'un point de vue chronologique et thématique, deux principaux résultats de recherche ont été obtenus. D'une part, la plupart des solutions proposées pour la conception pour la sécurité humaine interviennent assez tard dans le processus de conception. D'autre part, les solutions restantes ne prennent pas explicitement en compte les conditions d'application au cours des premières phases de conception.

2.7 Bilan de la littérature

Cette revue de la littérature a permis d'aborder de multiples aspects de la conception, de la santé et de la sécurité. Comme cela a été exposé, les différentes méthodes et théories de conception trouvées dans la littérature se concentrent sur des points de vue spécifiques qui négligent parfois des éléments cruciaux pour le succès de la solution finale. La plupart des processus de conception proposés par d'autres auteurs manquent d'exhaustivité si l'on considère que l'activité de conception ne repose que sur le projet ou le produit lui-même. Ce chapitre vise à montrer les recherches effectuées dans ce domaine, leurs résultats et la manière dont elles peuvent être appliquées dans une méthodologie différente qui regroupe leurs principaux éléments constitutifs et permet aux concepteurs de suivre une procédure de conception structurée, étape par étape.

La conception systématique se concentre trop sur le projet, ce qui laisse de côté d'autres aspects du processus de conception. Néanmoins, Pahl & Beitz ont établi le cadre principal d'un processus structuré à travers toutes les étapes de conception et constitue la base de la méthodologie proposée du point de vue du projet. DFSS a une approche intéressante des activités des concepteurs et propose des étapes chronologiques qui guident l'utilisateur pour obtenir le résultat attendu. Dans cette étude, une méthodologie générique de DFSS a été utilisée pour soutenir le point de vue des activités des concepteurs. L'ingénierie des systèmes est l'une des méthodes les plus complètes parmi celles étudiées, mais sa faiblesse réside dans le point de vue des activités du concepteur. Pour ce projet, il a été décidé d'utiliser l'approche produit proposée par l'ingénierie des systèmes car elle accorde une attention particulière au produit tout en étant compatible avec les autres aspects considérés pour le projet.

Comme le lecteur peut le constater, toutes les approches présentent des points forts et des points faibles et un large éventail de points de vue axés sur différentes parties de la conception. Ainsi, à partir de cette portée, l'idée de les appliquer simultanément pour avoir une méthode générale beaucoup plus complète se pose, mais ce n'est pas possible car elles ne sont pas assez compatibles pour être utilisées dans le même projet. Un des objectifs de cette thèse est de proposer une méthode qui inclut les aspects les plus utiles des méthodes décrites précédemment pour avoir une méthodologie robuste et utile à utiliser dans l'industrie.

En termes de méthodologie de conception, une décision a dû être prise parmi les différentes options présentes dans la littérature. L'une des deux options possibles était de combiner les méthodologies les plus performantes de chaque approche (projet, produit et raisonnement de conception) pour obtenir une méthodologie de conception complète. Cependant, le problème de cette solution est l'incompatibilité de la plupart des méthodologies trouvées dans la littérature. La deuxième option était d'enrichir la ou les méthodologies les plus homogènes pour avoir une base solide. Cette dernière option a été choisie pour les étapes suivantes. Ainsi, sur la base de l'analyse effectuée dans ce chapitre, les méthodologies les plus homogènes suivant l'axe d'analyse sont l'ingénierie système et la conception systématique.

Les approches d'intégration du facteur humain ne donnent que des lignes directrices pour la conception des systèmes de production, et seules quelques études ont proposé des cadres de conception collaborative de la sécurité. Cette conclusion suggère qu'il est nécessaire d'analyser les paramètres requis pour une évaluation de la sécurité et de les regrouper dans un cadre de conception général. La caractérisation énergétique doit être utilisée pour modéliser le comportement du système afin d'intégrer les facteurs de sécurité humaine et l'évaluation. Les approches de planification de projet présentent un cadre de conception approprié comme ligne directrice principale pour une méthode de conception intégrée. Les phases bien définies proposées dans ces théories fournissent une base solide pour intégrer des éléments d'autres approches. Les théories de raisonnement de conception donnent au concepteur des outils analytiques applicables tout au long des différentes phases d'un cadre général de conception. Ces outils représentent des actions ou des activités qui conduisent à des solutions pratiques aux problèmes de conception, qui peuvent être appliquées de manière itérative dans différents contextes. La conception par modélisation du produit donne des objectifs à atteindre en termes de temps, de coût et de performance, directement liés au produit incorporé dans un cadre général. Ces résultats ont été intégrés dans la méthode proposée, présentée et expliquée dans les chapitres suivants.

3. Processus et raisonnement de conception

3.1 Processus de conception

La méthode proposée est basée sur une version modifiée des phases proposées par [Pahl et al. 2007]. La thèse se concentre sur les deux premières phases du processus de conception : la définition du cahier des charges et la conception architecturale. La décision de se concentrer sur ces deux phases est basée sur l'importance de définir une base solide pour tout projet de conception et sur le fait que les objectifs, les exigences et les contraintes doivent être entièrement définis dans les premières phases du processus de conception. Les décisions prises au cours des deux premières phases d'un projet ont un impact significatif sur les phases suivantes. Si l'on ajoute à cela le fait que le temps et, par conséquent, le coût du développement évoluent de manière exponentielle au fil des phases, il est possible de conclure que le succès d'un projet de conception dépend principalement de ces décisions. Les dernières phases ont été largement étudiées, et les méthodes actuelles fournissent des outils suffisants pour être appliquées après la phase de conception.

Pour comprendre l'approche proposée, il est nécessaire de définir deux concepts complémentaires, le système opérant et le système opéré (figure 3.2). Le système opérant est défini comme l'agrégation de plusieurs composants qui interagissent et exécutent des fonctions de base pour atteindre un objectif ou une mission spécifique. Le système opéré est défini comme l'agrégation de multiples parties prenantes qui interagissent avec les éléments du système opérant, qui l'affectent et sont affectés par lui. L'objectif de l'approche proposée est d'abord d'identifier le système opéré pour définir les limites du problème de conception et voir la zone d'action de la solution finale, et ensuite, de définir complètement les propriétés et les caractéristiques du système opérant (résultat final du processus de conception) et comment il affecte et est affecté par le système opéré.

L'apport de cette méthode repose d'une part sur les interactions entre les différents éléments qui composent le processus de conception et d'autre part sur l'exploitation de cette structure pour obtenir les informations nécessaires à la réussite du projet de conception. Ces informations sont obtenues et traitées dès les premières étapes du processus en évaluant l'environnement et l'état actuel du système de production, puis en caractérisant son comportement attendu. Les trois éléments présentés dans la revue de la littérature (phases de conception, modèle de système et activités de raisonnement de la conception) n'ont pas été pleinement intégrés dans les méthodes et théories de conception existantes, ce qui est l'une des raisons pour lesquelles l'approche proposée utilise un modèle de système basé sur l'énergie. L'introduction de l'énergie a deux objectifs principaux : premièrement, faciliter la transition de l'architecture fonctionnelle à l'architecture organique (discutée au chapitre 4), et deuxièmement, faciliter les analyses telles que celles sur la sécurité des opérateurs (discutée au chapitre 5).

Pour expliquer les changements et les modifications, la proposition de conception systématique originale des deux premières phases est expliquée dans les sections suivantes, puis la nouvelle proposition est présentée sur la base des modifications et des critères proposés. Un aspect qui mérite d'être mentionné est que l'objet d'étude de la méthode proposée est spécifiquement un système de production. En revanche, l'approche systématique considère le produit comme l'objet d'étude. Cette différence fait que dans l'approche systématique, l'accent est mis sur l'utilisation du produit, alors que dans l'approche proposée, l'accent est mis sur les propriétés du système de production lui-même, le produit qu'il va produire, et les processus de fabrication impliqués.

3.1.1 Définition du cahier des charges

La définition du cahier de charges de l'approche systématique expose les principaux éléments à prendre en compte pour définir une liste d'exigences. Cependant, elle ne fournit pas un ensemble structuré d'étapes à suivre pour définir entièrement une liste d'exigences exhaustive qui contient les informations nécessaires pendant les différentes phases et étapes du processus de conception. Il y a l'aspect exhaustivité, mais aussi l'aspect perception. Il est important de noter qu'un client perçoit ses besoins à travers le filtre de sa culture et de ses expériences. Il en va d'ailleurs de même pour le designer. Il est donc essentiel que tous deux s'accordent sur une perception commune du besoin. La généralisation de la phase de définition du cahier de charges est compréhensible, étant donné que chaque projet de conception a des objectifs, des exigences et des contextes différents. Cependant, il existe de nombreux éléments communs qui fournissent une corrélation suffisante pour proposer une méthodologie standardisée pour définir la liste des exigences en fonction des besoins, des contraintes et du contexte du client.

- Analyse du système existant (CSA)

L'objectif principal de cette étape est de déterminer les besoins actuels du système. En considérant l'hypothèse qu'il existe déjà un système de production installé, l'objectif est de modéliser les fonctions et les contraintes pour déterminer les besoins du client en termes de temps, de coût et de performance. Une attention particulière doit être accordée au niveau de détail et de complexité du modèle car toutes les données recueillies doivent être utilisées dans les phases suivantes.

- Analyse du système attendu (ESA)

L'objectif principal du système attendu est de définir les limites du système opérant dans le contexte du problème de conception. Ces limites fournissent les informations nécessaires à l'équipe de conception pour développer une solution adaptée aux besoins du client. C'est pourquoi l'objectif de cette étape est de définir le système idéal qui peut répondre aux exigences du client. Pour définir ce système, il est nécessaire d'identifier les composants, les fonctions et les interactions à supprimer ou à modifier et d'identifier ceux à générer pour répondre aux exigences.

- Analyse du système opérant (OSA)

Cette étape vise à définir le système requis en se basant sur les différences entre le système existant et le système attendu. Le système opérant est formé par des composants et des interactions nouveaux ou modifiés qui répondent aux exigences des clients. Cette description se fait en trois temps, d'abord la mission du système opérant, et son cycle de vie sont spécifiés. Ensuite, les parties prenantes de l'environnement et les fonctions de base sont identifiées. Enfin, les connexions entre les contraintes techniques liées aux parties prenantes et aux Fonctions de base sont établies pour déterminer dans quelle mesure elles s'influencent mutuellement.

3.1.2 Conception architecturale

Cette sous-section décrit la deuxième phase de conception : la phase de conception de l'approche proposée. Durant cette phase, l'introduction des flux d'énergie pour les interactions entre les éléments devient nécessaire pour trouver des solutions techniques basées sur le transport, le stockage et la conversion de l'énergie. L'objectif principal de la conception architecturale est de réduire les solutions techniques possibles sur la base du modèle général déjà défini. La figure 3.9 montre la subdivision de la conception architecturale où le système opérant est entièrement défini.

En considérant le type d'énergie requis pour une fonction spécifique et le type d'énergie disponible, il est possible de choisir la solution la plus adaptée en termes de coût, de performance et de sécurité (voir chapitre 5). Le résultat attendu de cette phase est un modèle conceptuel du système avec des solutions techniques déjà définies. Cette phase est également divisée en trois étapes : Caractérisation automatique, Caractérisation énergétique, et Sélection des composants. Pour faciliter la transition entre l'architecture fonctionnelle et organique, il est nécessaire de décomposer les fonctions de base en sous-fonctions basées sur un modèle comportemental.

- Caractérisation automatique

Pour contrôler, commander et fournir de l'énergie aux Fonctions de Base et obtenir le résultat escompté, il est nécessaire de définir un ensemble différent de fonctions spécifiques à ces tâches. Ces fonctions sont des Fonctions Techniques Automatiques (FTA) nécessaires pour assurer la performance des Fonctions de Base et compléter l'architecture fonctionnelle du système. L'objectif est d'identifier les ATF pour chaque fonction de base à partir de catégories prédéfinies. Cette classification simplifie la transition entre l'architecture fonctionnelle et organique pour les étapes suivantes. Il existe quatre types d'ATF :

- Contrôle : détermine l'écart entre la sortie attendue et la mesure.
- Commande : détermine le signal à envoyer aux composants en fonction de l'écart entre la sortie attendue et la mesure.
- Alimentation en énergie : fournit de l'énergie aux composants pour exécuter des fonctions de base ou techniques.
- Action : utilise l'énergie du système pour exécuter les fonctions de base.

- Caractérisation énergétique

Pour définir et modéliser l'architecture organique du système, il est essentiel de définir son comportement. Cette étape vise à modéliser le comportement du système par le traitement du flux d'énergie à l'intérieur du système, qui peut également fournir les informations nécessaires à une évaluation de la sécurité. Ce traitement a été défini comme un ensemble de fonctions techniques énergétiques (ETF) nécessaires pour atteindre les résultats attendus des fonctions de base d'un point de vue énergétique. Les ETF sont des actions qui transportent, convertissent ou transforment l'énergie à l'intérieur du système. Elles sont la caractérisation des fonctions en termes de manipulation et de traitement de l'énergie. C'est pourquoi la distribution de l'énergie doit être identifiée sur la base des ATF définies à l'étape précédente. Les ETF sont déterminés par les différents flux d'énergie qui existent à l'intérieur du système. Il existe trois types d'ETF :

- Le transfert : guide et déplace un flux d'énergie d'un point donné à un autre.
- La conversion : modifie la nature et les propriétés d'un flux d'énergie.
- Transformation : modifie les propriétés d'un flux d'énergie sans en changer la nature.
  - Sélection des composants

La sélection des composants est la dernière étape de la phase au cours de laquelle l'architecture organique de la solution finale est réalisée. Dans cette étape, les exigences définies lors de la définition du cahier de charges deviennent les critères finaux pour évaluer l'aptitude d'un composant à accomplir une fonction requise. Cette sélection est effectuée à l'aide des ETF et des catalogues normalisés classés par traitement énergétique. Il existe deux catégories de composants : standard et spécifique. Les premiers peuvent être directement sélectionnés dans des catalogues proposant une classification par caractéristiques énergétiques. Dès que ce travail sera effectué, ils seront parfaitement connus (performance, géométrie, coût). Quant aux seconds, ils poursuivront le processus de conception jusqu'au bout. Pour les composants spécifiques qui n'ont pas été normalisés, il est nécessaire de définir tous ses paramètres. C'est pourquoi il est toujours préférable de choisir un composant normalisé.

3.2 Activités de raisonnement de conception

3.2.1 Spécifier

Dans Specify, l'objectif est de définir les informations nécessaires pour les activités suivantes. Ces informations sont obtenues à partir des étapes précédentes du projet ou du client et de l'environnement de conception. Pour spécifier ces informations, il est nécessaire de fixer des résultats attendus ou des objectifs à atteindre après avoir traité ces informations. Ces objectifs peuvent être décrits en termes de valeurs cibles ou d'une liste d'informations requises liées aux caractéristiques et aux propriétés du système, telles que celles proposées sur CPM [Weber et al. 2003 ; Weber 2005, 2009]. Les caractéristiques décrivent la structure, la forme et la cohérence du système sur lesquelles le concepteur peut agir directement. Les propriétés décrivent le comportement du système, mais celui-ci ne peut pas être affecté directement par le concepteur ; il ne peut l'être qu'indirectement en modifiant les caractéristiques.

3.2.2 Conception

Dans la conception, l'objectif est d'utiliser les informations collectées pour concevoir des concepts généraux pour l'objectif proposé précédemment. Cette conception fait référence au fait de créer de nouvelles informations ou connaissances à partir de données préliminaires. Dans cette étape, les concepts ou les éléments ne sont pas entièrement définis mais fournissent une base solide pour les activités suivantes. Les concepts précédents sont structurés pour créer une représentation entièrement définie des concepts ou des éléments au cours du modèle d'activité. En fonction de l'objectif intermédiaire et des éléments manipulés, différents modèles peuvent être utilisés, par exemple, une matrice de relations pour relier les fonctions de base aux contraintes techniques ou un graphe de séquence qui montre les interactions entre les éléments au cours d'un temps. Si l'on considère les deux types de relations proposés par Weber dans le CPM, l'analyse et la synthèse, la nature des relations entre les éléments dépendra de l'objet d'étude dans l'activité du modèle de la méthode proposée. Les relations du système existant émergent d'un processus d'analyse des caractéristiques connues, tandis que celles du système opérant sont dérivées d'un processus de synthèse, ayant entre les deux le système attendu qui est un mélange des deux.

3.2.3 *Modélisation*

Cette activité est directement liée à la modélisation du système, qui est le sujet principal du chapitre 4. Néanmoins, dans cette sous-section, une petite introduction des aspects à considérer est faite. La première étape du modèle consiste à créer la structure physique des objets intermédiaires. La définition de la structure physique a pour but de servir de catalyseur pour les travaux ultérieurs de conception et de conception détaillée visant à réaliser ce potentiel maximal. La méthode de conception axiomatique utilise un modèle en zigzag pour créer des structures physiques et de processus. La structure est représentée mathématiquement par le regroupement de matrices appartenant au même niveau hiérarchique. La hiérarchie est construite en déconstruisant la conception en une série de matrices de conception fonctionnelle plus simples qui satisfont collectivement les exigences fonctionnelles. Il faut vérifier l'indépendance de la matrice des FR, c'est-à-dire s'assurer qu'elles sont distinctes et uniques les unes des autres. Par exemple, la vitesse et le couple sont des exigences fonctionnelles indépendantes les unes des autres, bien que la physique les lie. Cette exigence est nécessaire car elle établit, à des fins de conception, un ensemble minimal capable de répondre aux exigences de conception. Le client peut ne pas demander d'exigences fonctionnelles supplémentaires, ce qui entraîne une conception excessive ou une proposition de valeur sous-optimale pour le client.

3.2.4 *Évaluer et optimiser*

L'activité Évaluer et optimiser est nécessaire pour réduire les itérations du processus de conception car elle permet d'améliorer progressivement chaque aspect de la solution finale au fur et à mesure de son développement. En outre, cette activité permet d'introduire différents critères, tels que les facteurs de sécurité. L'objectif de l'évaluation et de l'optimisation est de passer en revue la liste des exigences de conception et de les comparer aux résultats de la solution finale. En outre, un indice d'importance doit être inclus pour chaque élément de la liste. Par exemple, dans la conception d'un véhicule ou d'un avion, tout besoin lié à la sécurité doit recevoir un rang de priorité très élevé.

3.2.5 *Valider*

La dernière étape, la validation, sert à approuver le modèle optimisé en fonction des critères de temps, de coût et de performance ou de tout autre aspect qui doit être validé dans la solution finale. La validation de la conception est une technique qui confirme que les conceptions optimisées du système et du processus s'exécutent au niveau spécifié par le client. La conception du système doit être vérifiée dans les domaines suivants :

1. Validation de la performance fonctionnelle.

2. Validation des exigences environnementales opérationnelles.

3. Validation des critères de fiabilité.

4. Validation des exigences d'utilisation.

5. Validation des exigences de sécurité.

6. Validation des interfaces et de la compatibilité.

7. Validation de la nécessité de la maintenabilité.

Tous les systèmes ne nécessitent pas toutes ces validations. Les besoins en matière de validation et la pertinence relative de chaque type d'activité de validation varient considérablement d'un système à l'autre ; une analyse des besoins en matière de validation doit être entreprise pour générer une liste de tous les éléments de validation.

3.3 Synthèse et intégration

Comme il a été exposé dans ce chapitre, la méthode proposée utilise une version modifiée du cadre général de conception proposé dans les théories de conception pilotée par projet [Pahl & Beitz 1996 ; Pahl et al. 2007], composé de quatre phases différentes : Définition du cahier des charges, Conception conceptuelle, Conception détaillée et Évaluation de la fabrication. Les phases et étapes proposées fournissent un cadre de conception bien structuré basé sur la conception pilotée par projet et le raisonnement de conception qui va du besoin de base à la solution finale, permettant au concepteur d'introduire des outils de prise de décision liés à une expertise spécifique (sécurité humaine). L'intégration des activités de raisonnement de conception permet d'avoir une représentation du processus de conception sous forme de matrice, comme le montre la figure 3.15. Cette représentation proposée fournit une séquence logique pour chaque décision à prendre pendant la conception. La nature oscillante des différentes activités que doit suivre l'équipe de conception fournit toutes les informations nécessaires pour planifier le développement du processus de conception. L'utilisation d'un diagramme de Gant pour représenter la durée de chaque étape et les activités de conception itératives comme référence permet de définir complètement la planification du projet du problème de conception. Il s'agit d'une approche qui n'a pas encore été explorée dans la littérature et qui enrichit les théories de conception actuelles, en reliant le cadre général aux tâches de conception de base.

La figure 3.15 montre les trois éléments qui forment le cadre intégré : les phases sous forme de flèches horizontales, les étapes sous forme de subdivisions des phases, et les activités de raisonnement de conception sous forme de flèches verticales sur le côté gauche. Chaque élément de la matrice représente une tâche de conception de base qui est séquencée par le comportement oscillant du développement du projet. Cette représentation sous forme de matrice est proposée pour identifier les tâches de conception de base qui intègrent les trois points de vue discutés dans la revue de la littérature.

4. Modélisation du système

4.1 Le concept de système

Le terme système est utilisé pour représenter des groupes d'éléments et d'interactions d'une manière abstraite qui en facilite la compréhension. C'est un bon point de départ pour définir un problème de conception car il est indépendant de la solution. Un système est décrit comme un ensemble d'éléments en interaction structurés pour atteindre un ou plusieurs objectifs déclarés [ISO/IEC 2008 ; INCOSE 2010]. Lors de la définition d'un système, trois concepts doivent être pris en compte : les exigences, la portée et l'architecture [Faisandier 2011]. En termes de services et de restrictions, les exigences font référence aux résultats attendus du système, qui sont le principal résultat de la définition des exigences. La portée d'un système fait référence à ses limites, à ce qu'il inclut et à la façon dont il interagit avec le reste du monde. Le terme architecture fait référence à la clarification de la structure opérationnelle et physique d'un système (c'est-à-dire l'organisation des composants).

4.1.1 Exigences

Comme indiqué par [Ross & Schoman 1977], la spécification des exigences doit expliquer pourquoi un système est nécessaire, sur la base de circonstances présentes ou futures, y compris les opérations internes ou un marché externe. Elle doit spécifier les caractéristiques du système qui seront utiles et satisfaisantes dans cette situation. Elle doit également spécifier comment le système sera construit. Lorsqu'une usine a besoin d'un nouveau système de production pour s'adapter à la fabrication d'un nouvel ensemble de produits, il lui faut plus qu'une nouvelle structure. Elle aura besoin de nouvelles fonctions de base à exécuter par des humains ou des machines, de nouvelles fonctions techniques pour contrôler, commander et fournir de l'énergie à ces fonctions de base, d'éléments de sécurité pour protéger les humains et les machines à proximité, de chaînes d'approvisionnement à adapter au nouveau système de production, des différentes phases de son cycle de vie, des parties prenantes et de leur impact sur le système ainsi que l'inverse.

4.1.2 Contexte

Le premier élément à considérer pour un système est son contexte, nécessaire à la compréhension de son environnement. Le contexte est représenté par l'environnement dans son état actuel (c'est-à-dire sans le système). Selon l'ingénierie des systèmes, l'environnement est le milieu (naturel ou artificiel) dans lequel le système d'intérêt est utilisé et soutenu, ou dans lequel le système est développé, produit ou retiré [INCOSE 2010]. Le terme d'environnement est fréquemment remplacé par celui de domaine en ingénierie logicielle, notamment dans l'approche des cadres de problèmes [Jackson & Zave 1993]. La notion d'ingénierie système est implicitement limitée aux éléments physiques, mais le concept de domaine est plus large, englobant les artefacts intangibles tels que les informations ou le savoir-faire. Les domaines suivants s'ajoutent au concept d'environnement : l'indépendance du système, la nature plus large de l'environnement, et une différenciation entre l'état actuel et futur. Dans les normes de génie logiciel [IEEE 2010], certains de ces aspects sont utilisés pour établir l'idée d'environnement.

4.1.3 Architecture

Le terme architecture fait référence à la clarification de la structure fonctionnelle et physique d'un système (c'est-à-dire l'organisation des composants). La figure 4.5 montre la zone d'intérêt pour la définition de l'architecture. Dans ce cas, l'accent sera mis sur le système opérant, les éléments internes et les attributs physiques. Un système est considéré comme une boîte blanche (Figure 4.6) lorsqu'on travaille avec son architecture, avec tous ses composants visibles et observables. Comme indiqué dans la taxonomie de la gestion de la valeur, les composants d'un système sont appelés éléments internes au lieu d'éléments externes [AFNOR 1996]. Il faut néanmoins distinguer l'élément interne et la ressource. Dans cette étude, une ressource peut être soit interne, soit externe au système. Les deux termes font allusion à des points de vue opposés mais complémentaires. Les termes Élément interne et Élément externe font référence au système global, tandis que la ressource est un composant physique qui peut être appelé à répondre partiellement ou entièrement à une ou plusieurs fonctions du système opérant. Un élément interne est tout objet physique ou non physique dont l'existence dépend entièrement de celle du système et contribue à son bon fonctionnement.

4.2 Modèle de système proposé : Behavior-Energy-Structure (BES)

Au cours des premières phases de conception, des informations spécifiques sont nécessaires pour évaluer des paramètres particuliers définis par le client et le maître d'ouvrage. Ces paramètres changent en fonction de l'objectif du projet de conception, et il est essentiel de pouvoir identifier les informations requises dans le cadre du processus de conception. Par exemple, pour cette étude, l'un des objectifs est de fournir une intégration adéquate de la sécurité humaine dans les premières phases de conception. Dans la revue de la littérature, certaines études ont utilisé le flux énergétique pour l'évaluation de la sécurité des systèmes de production [De Galvez et al. 2017]. L'énergie est un élément générique et commun à l'architecture fonctionnelle et organique. Elle est, par conséquent, un vecteur privilégié de passage d'une architecture à une autre. Elle facilite donc la conception.

De plus, elle représente également un élément important dans l'analyse de la sécurité, comme vu dans la revue de littérature. Cela facilitera donc la collecte de données pour l'analyse de la santé et de la sécurité. L'utilisation de l'énergie fournit suffisamment d'informations pour définir l'architecture organique du système et une base solide pour effectuer les évaluations de sécurité. L'application de la BES se fait par le biais des fonctions techniques énergétiques qui apparaissent dans la deuxième phase de la méthode en utilisant les informations recueillies lors de la définition du cahier de charges. Cependant, cette approche est représentée tout au long des activités de modélisation en utilisant une combinaison des trois concepts discutés dans la revue de la littérature. La séquence logique permet de définir complètement un modèle de système basé sur ses fonctions, son comportement et sa structure.

4.2.1 Comportement

Dans cette étude, la notion de comportement est utilisée pour structurer les nombreux éléments issus des phases et étapes de conception abordées au chapitre 3, ainsi que pour introduire une nouvelle construction complémentaire. Il est nécessaire de distinguer le comportement lié à l'architecture fonctionnelle de celui lié à l'architecture organique. La première est représentée par les caractéristiques de la mission, les fonctions de base et les fonctions techniques automatiques. Le second est représenté par les caractéristiques des Fonctions Techniques Energétiques et des Composants.

4.2.2 Energie

Dans cette étude, la notion d'énergie est utilisée pour décrire l'ensemble des sources et des flux d'énergie liés au système (internes et externes). Cette caractérisation énergétique permet de décrire le comportement interne du système à travers les fonctions énergétiques. L'énergie se présente sous différentes formes et tailles. Sa forme naturelle, ou la forme qui lui est imposée, renseigne sur ses applications potentielles. L'énergie relie systématiquement le comportement et les éléments physiques. En d'autres termes, entre le fonctionnel et l'organique. Cette caractéristique permet fondamentalement de guider le passage de l'un à l'autre (ce que le modèle "FBS" ne permet pas de faire, par exemple). De plus, accessoirement, l'énergie fournit également les informations nécessaires à l'analyse de la sécurité lors de la conception.

4.2.3 Structure

Dans cette étude, la notion de Structure est utilisée pour rassembler l'ensemble des constructions qui caractérisent les composants d'un système et leur agencement. Elle fait référence aux composants, qui sont statiques. La structure est décrite par les attributs caractéristiques des composants, qui sont ceux qui peuvent être directement contrôlés ou décidés par le concepteur (par exemple, le matériau, la forme, les proportions) [Weber 2005]. Dans certaines théories de conception, ils sont appelés qualités internes [Eder 2008] ou paramètres de conception [Suh 1990].

4.3 Discussion et conclusion

L'approche de modélisation énergétique présentée dans ce chapitre complète la méthode proposée en fournissant les outils pour représenter le comportement, l'énergie et la structure du système opérant. La représentation du comportement est directement liée à l'architecture fonctionnelle du système, et la représentation structurelle est directement liée à son architecture organique. Le passage entre ces deux architectures se fait par la caractérisation énergétique, qui d'une part, complète l'architecture fonctionnelle et, d'autre part, fournit les informations nécessaires au choix des composants du système opérant.

La dynamique entre l'architecture fonctionnelle et l'architecture organique est toujours un point critique de chaque projet de conception car les approches de conception actuelles ne traitent pas ce passage en profondeur, et la plupart du temps, c'est à l'expérience et aux connaissances de l'équipe de conception de faire cette transition. L'approche proposée apporte une solution à ce dilemme récurrent, qui devient l'une des contributions de la méthode.

Le modèle de système est crucial pour le processus de conception car il reflète tous les changements et toutes les décisions prises au cours des différentes étapes et phases pour atteindre le résultat attendu. En ce sens, le modèle de système influence grandement le processus de conception car il fournit un ensemble d'objectifs intermédiaires à atteindre. L'identification d'autres approches de modèle de système définies dans la littérature a permis d'identifier le bon ensemble d'objectifs à utiliser dans la méthode proposée. L'approche basée sur l'énergie est le résultat de cette analyse.

De plus, la caractérisation énergétique sert à la fois d'outil pour définir et compléter le système et de source d'information nécessaire pour effectuer différents types d'analyse en utilisant les mêmes informations obtenues pour le processus de conception. Comme discuté dans cette étude, l'accent est mis sur la sécurité humaine pendant la conception des systèmes de production, et la modélisation énergétique permet parfaitement l'utilisation de méthodes et d'outils d'évaluation de la sécurité pendant le processus de conception. Dans ce chapitre, cette intégration a été discutée brièvement, mais le chapitre 5 aborde une analyse plus approfondie.

Dans le chapitre suivant, la méthode de conception proposée est entièrement définie sur la base de tous les éléments qui ont été discutés. Une étude de cas est utilisée pour décrire et valider l'application de la méthode, et les éléments nécessaires à l'intégration de la sécurité sont discutés.

5. Méthode de conception proposée, intégration de la sécurité, et illustration sur un cas d’étude

5.1 Étude de cas

Ce chapitre montre l'application séquentielle de la méthode proposée sur un poste de soudage semi-automatique, qui fait partie d'un système de production existant dans une usine de la région. L'objectif est d'expliquer l'application du processus de conception étape par étape et toutes les considérations à prendre en compte en fonction des différents éléments discutés dans les chapitres précédents et des aspects spécifiques de l'étude de cas. Il est important de préciser que l'objectif de la conception est de proposer une solution aux besoins du client sur la base du poste de travail préexistant dans ce cas. Cela signifie que le choix de la solution finale sera affecté par les ressources disponibles (composants et pièces actuels), mais qu'elles ne le limiteront pas.

Le poste de travail de soudage (figure 5.1) est divisé en deux, la zone de soudage et la zone d'alimentation. La zone d'alimentation est l'endroit où l'ouvrier charge les pièces non soudées pour les acheminer vers la zone de soudage et où les pièces finies sont déchargées pour être envoyées au poste suivant. Il existe deux râteliers différents pour les pièces soudées et non soudées afin de stocker les pièces avant et après le processus de soudage. L'opérateur est chargé de déplacer les pièces du rack vers la table rotative et de les fixer sur la table à l'aide de différentes broches ou pinces en fonction de la référence de la pièce. De même, l'ouvrier est chargé de libérer les pièces soudées du cycle de soudage précédent et de les ranger dans le rack qui leur a été attribué. Le robot effectue une trajectoire de soudage spécifique dans la zone de soudage en fonction du type de pièces fixées sur la table. Les deux zones sont physiquement séparées par une barrière de protection, et une table rotative placée entre les deux zones effectue les échanges de pièces.

Le problème exprimé par le client était l'équilibre temporel entre les activités de l'ouvrier et la soudure automatique effectuée par le robot. Dans le système existant, l'ouvrier prend plus de temps pour réaliser la tâche que le robot, ce qui implique des temps morts itératifs sur la zone de soudage.

5.2 Définition du cahier de charges pour le poste de soudage

La première phase du processus de conception commence par la définition de la tâche de conception. Dans ce cas, l'objectif est de déterminer le périmètre de l'étude pour le poste de soudage, de modéliser ses caractéristiques actuelles pour les utiliser comme point de départ de la conception du système opérant, et de fournir les exigences techniques nécessaires à la solution finale.

Cette section décrit l'application des trois étapes qui composent la définition du cahier de charges et illustre l'utilisation des cinq activités de raisonnement de conception qui apparaissent de manière itérative sur chaque étape. Pour la première étape (Analyse du système existant), seules trois activités de raisonnement de conception sont considérées en raison de la nature de l'étape : spécifier, modéliser et valider. La première étape ne nécessite pas les activités de conception ou d'évaluation et d'optimisation car elle est destinée à montrer l'état actuel du système de production ou, dans ce cas, du poste de travail. Dans le cas de la conception d'un nouveau système de production pour lequel aucune information préalable n'est disponible pour servir de point de départ, il est possible de commencer le processus de conception par la définition du système attendu. Pour les deux autres étapes de cette phase, toutes les activités de raisonnement de la conception sont prises en compte.

5.3 Conception du poste de soudage

La deuxième phase du processus de conception vise à choisir les principes de fonctionnement et les composants de la solution finale. Les fonctions de base identifiées lors de la phase précédente correspondent à un besoin fonctionnel, et il est maintenant nécessaire de définir le comportement associé à travers deux autres types de fonctions. Cette phase détermine la faisabilité du projet de conception en fonction des solutions possibles et de leur conformité aux besoins, contraintes et exigences techniques du client. Cette section décrit l'application des trois étapes qui composent le conception architecturale et illustre l'utilisation des cinq activités de raisonnement de conception qui apparaissent de manière itérative à chaque étape.

5.4 Intégration de la sécurité

Comme indiqué au chapitre 1, les facteurs humains et la sécurité sont des éléments essentiels de la conception des systèmes de production en raison de l'influence des actions et du comportement des travailleurs sur les performances globales du système. L'identification des risques pour la sécurité le plus tôt possible au cours des phases de conception est une exigence pour un cadre général de conception. Cette identification doit être effectuée en utilisant les informations du système disponibles pendant le processus de conception. Pour cette tâche, certains travaux de recherche ont utilisé des modèles de produits basés sur l'énergie comme outils dédiés à l'évaluation de la sécurité. Dans l'approche proposée par [Gomez Echeverri et al. 2020], le modèle de système basé sur l'énergie est polyvalent car il définit entièrement le comportement du système et fournit les informations nécessaires à l'analyse des facteurs humains et de la sécurité. L'intégration d'outils de prise de décision peut également être adaptée à d'autres types d'expertise, comme la conception durable.

La méthode proposée par [Gomez Echeverri et al. 2020] peut être adaptée pour fonctionner avec le cadre de conception proposé dans ce manuscrit. Les valeurs d'entrée et les informations nécessaires pour effectuer l'analyse de sécurité sont complètes après l'étape de sélection des composants. Sur la base du modèle du système opérant et des propriétés de ses composants, il est possible d'utiliser un logiciel de CAO pour évaluer le niveau de risque pour un travailleur humain à l'intérieur du système.

5.5 Résultats et discussion

L'utilisation de l'approche de modélisation du système, soutenue par un cadre de conception défini, a été démontrée dans ce chapitre. La séquence de traitement des éléments de l'étude est fournie de manière logique et systématique dans cette étude de cas. La méthode est systématique lors de l'application des différentes phases et étapes de conception, et elle contribue à l'élaboration du modèle de système et de toutes les propriétés et caractéristiques de ses composants. La contribution de cette technique est basée sur la détermination des demandes réelles du client à partir de l'état existant du système de production et de la définition des composants basée sur une approche énergétique employant le comportement des fonctions et le flux d'énergie à travers la structure du composant. Le dernier chapitre du manuscrit discute des possibilités de recherches futures sur ce sujet.

Comme nous l'avons démontré, il existe de nombreuses théories de conception d'un système de production, chacune d'entre elles utilisant un ensemble différent de principes pour le processus de conception. Certaines d'entre elles se préoccupent davantage du projet lui-même, en utilisant un cadre strict d'activités séquentielles, tandis que d'autres mettent davantage l'accent sur les qualités du produit pour résoudre le problème de conception, en laissant de côté le cadre du projet. Comme il n'existe pas de théorie générale de conception qui tienne compte de la planification du projet, de la caractérisation du produit et du raisonnement de conception, le concept de développement d'une méthode intégrée qui combine ces trois parties pour concevoir des systèmes de production plus fiables émerge.

Au final, la méthode ne fait appel qu'à trois types de formalisme différents : Formalisme du système existant (modèle entité-relation structuré en fonction du temps) ; Formalisme du besoin du client (cartes mentales et matrice de liens) ; Formalisme de l'architecture (modèle entité-relation appliqué à BF, ATF, ETF et EC). Ces trois formalismes simplifient la modélisation de systèmes complexes et fournissent les informations nécessaires à l'équipe de conception lors du développement de la solution finale.

L'objectif de ce chapitre était de présenter le travail effectué sur ce sujet d'étude en présentant une méthode de conception pour les systèmes de production. Cette méthode reprend certaines des idées clés d'autres théories de conception et les combine pour mettre l'accent sur la formalisation du désir du client de produire un système de production qui réponde à ses besoins. L'une des contributions de cette méthode aux théories de conception contemporaines est l'approche énergique utilisée par BES pour passer des fonctions fondamentales aux composants.

6. Conclusions

6.1 Problèmes et questions de recherche fondamentales

Cette première section résume les objectifs généraux de la recherche et la méthodologie utilisée pour développer la méthode de conception proposée. L'objectif est de rappeler ces objectifs et d'évaluer s'ils ont été atteints avec les résultats de ce travail de recherche. Comme présenté au chapitre 1, l'objectif de ce projet de recherche était de proposer un cadre de conception multicritères pour concevoir des systèmes de production complexes et multi-technologiques qui répondent aux exigences de conception tout en étant suffisamment flexibles pour intégrer d'autres exigences telles que la sécurité humaine ou la durabilité. Les exigences de sécurité ont été utilisées comme critères de décision dans ce travail afin de démontrer l'intégration tout au long du processus de conception.

L'objectif général de la recherche a été résumé par la question suivante : Comment concevoir un système de production intégrant la sécurité des opérateurs tout en respectant tous les objectifs de conception en termes de temps, de coût et de performance ? A partir de cette question, trois problématiques scientifiques ont été définies afin de répondre à cet objectif :

- Question 1 : Comment définir un cadre de conception permettant de gérer de manière cohérente le processus de conception, la modélisation du système et le raisonnement de conception ?
- Question 2 : Comment définir une méthodologie d'analyse des risques liés à la sécurité des travailleurs du système de production ?
- Question 3 : Comment établir une connexion entre les données de conception et les outils d'analyse des risques pour prendre en compte la sécurité des opérateurs le plus tôt possible dans la conception des systèmes de production ?

Ces questions scientifiques ont été classées en trois grandes catégories : méthodologie de conception, identification des risques pour la sécurité et intégration de la sécurité dans la conception. Alors que les deux premiers aspects nécessitaient une analyse indépendante, le troisième était basé sur la compatibilité des deux autres.

Le premier aspect était lié aux diverses composantes des théories et méthodes de conception. Il a fallu rechercher et analyser diverses approches de conception pour déterminer leur applicabilité et définir les différentes phases, activités et modèles de conception. Ces éléments se sont avérés suffisamment adaptables pour permettre l'intégration de diverses approches de conception et d'outils de prise de décision complémentaires.

La deuxième question visait à définir un outil générique d'analyse des risques capable de prendre en compte l'effet d'un environnement industriel sur la sécurité humaine. L'objectif était de décrire une approche d'identification des risques pouvant être utilisée au cours des premières étapes du processus de conception d'un système de production. La compatibilité des approches du risque et de la conception a été examinée en fonction de l'endroit et du moment où ces approches étaient applicables et du moment où l'information requise était disponible dans le processus de conception.

Enfin, la troisième question a établi l'objectif principal de la thèse. L'intégration de l'analyse des risques et de la conception du système de production nécessitait un cadre général permettant une flexibilité de conception tout en maintenant la solution finale suivant les exigences et les contraintes de conception.

Toutes ces questions ont été abordées dans ce projet dans le cadre de la méthodologie de recherche. Dans la sous-section suivante, les résultats du travail de recherche sont rappelés comme une synthèse de tous les éléments présentés dans ce manuscrit et comment ils se rapportent à l'objectif et aux questions de recherche.

6.2 Contributions

Les questions de recherche ont été abordées à l'aide d'analyses documentaires complètes (voir chapitre 2) et de l'application d'une étude de cas développée parallèlement à la méthodologie proposée. Une attention particulière a été accordée à l'étude des modèles de systèmes, de la modélisation des fonctions et des outils d'intégration de la sécurité proposés dans les approches de conception disciplinaires et interdisciplinaires.

6.2.1 Concernant la conception des systèmes de production et l'intégration de la sécurité

Comme nous l'avons vu, trois éléments principaux interviennent au cours de tout projet de conception : les exigences, le processus de conception et les outils (Figure 6.1). Ces éléments sont identifiés et appliqués par l'équipe de conception pour développer la solution finale au problème de conception. Le processus de conception a été abordé aux chapitres 3 et 4, tandis que l'intégration des outils de conception dans le processus de conception a été traitée au chapitre 5. Les exigences de conception ont été examinées par [Cochran et al. 2001], et leur impact sur les deux autres éléments est abordé dans la sous-section 2.2 de ce chapitre.

Pour répondre à la première question de recherche relative au processus et à la structure de conception, un cadre général a été proposé sur la base des phases de conception systématique, de la modélisation du produit/système de FBS et de la nature itérative des activités de raisonnement de conception. Le développement de ce cadre a été discuté dans les chapitres 3 et 4. Ce cadre est représenté dans un modèle matriciel (figure 6.1), qui introduit une compréhension différente du processus de conception. Cette représentation fournit des outils et des solutions spécifiques pour chaque aspect du processus de conception. La différenciation de chaque activité de conception pour chaque étape de conception permet l'intégration d'autres outils à des moments très spécifiques du processus, ce qui confère une flexibilité accrue à la méthode proposée en fonction du problème de conception. Par exemple, dans l'activité Évaluer et optimiser, il est possible d'intégrer différents critères pour évaluer une solution intermédiaire en fonction des besoins du client.

La deuxième question de recherche a été abordée en identifiant les approches et les outils d'intégration de la sécurité compatibles avec le cadre de conception proposé. Ces approches et outils ont été classés en fonction du type d'élément qu'ils représentent et des informations requises. Ces informations ont influencé la définition de la modélisation du système en déterminant les caractéristiques et propriétés à définir pour pouvoir utiliser les approches et outils de sécurité. L'identification des éléments à prendre en compte pour une analyse de sécurité a été abordée dans les chapitres 2 et 4.

La troisième et dernière question a été abordée par la définition du moment où les approches et outils de sécurité peuvent être appliqués dans le processus de conception et la nature itérative des activités de raisonnement de conception. Cela a permis de considérer les aspects de sécurité du système de production comme faisant partie du processus de conception. Cette intégration a été réalisée en utilisant les activités de raisonnement de conception qui, comme nous l'avons mentionné, peuvent être adaptées en fonction des besoins de la conception. Cette intégration a été discutée au chapitre 5.

La modélisation du système de l'approche a été définie par les éléments et les informations nécessaires aux différentes étapes du processus de conception liées aux objectifs de conception et de sécurité du projet. La caractérisation des différents éléments intégrés dans le modèle du système rend possible la prise en compte d'autres indicateurs clés de performance en utilisant un modèle unique.

L'application de la méthode proposée à un poste de soudage a fourni le retour d'expérience nécessaire pour valider l'approche. Le cas d'étude était un processus de conception basé sur un système de production préexistant, ce qui correspond à la majorité des cas de conception standard. Dans le cas d'une conception innovante, la méthode peut également être appliquée en changeant le point de départ de la modélisation du système. Cette flexibilité répond aux objectifs de conception du projet de recherche en fournissant un cadre général applicable à la plupart des problèmes de conception.

Comme la méthode a été appliquée à un cas d'étude réel, il a été possible d'identifier et de corriger certaines des lacunes du cadre. Pour concevoir des systèmes très complexes, la méthode peut nécessiter l'utilisation d'un grand nombre de diagrammes, ce qui peut rendre difficile l'emploi de cette technique. C'est l'une des directions dans lesquelles les futures initiatives de recherche devraient être orientées pour compléter la méthode.

6.2.2 Exigences du processus de conception

Plusieurs cadres ont été développés pour relier les décisions de bas niveau aux objectifs de niveau système. Ces cadres relient fréquemment divers outils de conception et de développement de la production aux objectifs d'une organisation de production. [Gilgeous & Gilgeous 1999] fournissent un cadre qui prend en compte quatre objectifs de performance de haut niveau du système de production (qualité, coût, livraison et flexibilité) ainsi que huit initiatives tactiques qui contribuent toutes à la réalisation de chaque objectif de performance. [Hopp & Spearman 2011] ont créé une hiérarchie des objectifs de production, en commençant par l'objectif de " haute rentabilité. " Comme le montre la figure 6.2, cette hiérarchie montre que la performance idéale du système de production est soumise à des compromis. Elle démontre également qu'une caractéristique de conception, un temps de cycle rapide (temps de passage), est liée à la réduction des coûts ainsi qu'à l'amélioration du service client. Ces techniques n'établissent pas une relation de conception forte entre les objectifs stratégiques et les moyens opérationnels pour les atteindre, et elles n'énoncent pas non plus les moyens d'atteindre les objectifs spécifiés. L'approche proposée définit ces objectifs stratégiques pendant la définition du cahier de charges et les moyens opérationnels pour les atteindre pendant la phase de conception.

La décomposition de la conception du système de fabrication (MSDD) proposée par [Cochran et al. 2001] stipule que la condition la plus importante pour tout système de fabrication est de maximiser le retour sur investissement à long terme. Dans ce contexte, le retour sur investissement à long terme (ROI) fait référence à l'ensemble du cycle de vie d'un système plutôt qu'aux quelques années à venir. Cette approche est basée sur la conception axiomatique et utilise les exigences fonctionnelles (FR) et les paramètres de conception (DP) pour définir les objectifs de conception. Dans la figure 6.3, la maximisation de la satisfaction du client (DP-11) est proposée comme stratégie d'augmentation des revenus. Ce DP a ensuite été déconstruit sur la base des aspects de performance critiques des systèmes de fabrication qui ont un impact sur la satisfaction du client : qualité de la conformité (FR-111), livraison à temps (FR112) et faible délai d'exécution (FR-113). La méthode spécifiée pour obtenir une qualité conforme garantit que les processus de production s'écartent le moins possible de l'objectif (DP-111). Au lieu de s'appuyer sur l'inspection finale pour éviter l'envoi de composants défectueux, la DP-111 se concentre sur l'amélioration des processus. A ce niveau de conception (illustré visuellement par des flèches sur la figure 6.3), l'obtention de la qualité de conformité (DP-111) est importante pour accroître la satisfaction du client. La variation de la qualité et la production de défauts rendent la sortie du système imprévisible, ce qui a un impact négatif sur la FR-112, "Livrer les produits à temps", et nécessite la production de pièces supplémentaires pour remplacer ces défauts, ce qui a un impact négatif sur la FR-113, "Respecter les délais prévus par le client." Une qualité de conformité élevée est nécessaire pour atténuer l'influence de la DP-111 sur la livraison prévisible et le délai d'exécution d'une conception de système de fabrication.

En observant les objectifs de conception et la manière dont cette approche propose leur définition, il est possible de dire que la manière de relier les décisions de bas niveau aux objectifs de niveau système repose davantage sur un niveau de granularité plus élevé de l'entreprise du client. Dans le cas de l'approche proposée, le niveau de granularité définit le périmètre du projet de conception et évite la modélisation d'aspects du système qui ne sont pas pertinents pour le problème de conception en question. Il est également possible de dire que de multiples solutions peuvent être trouvées en fonction du niveau de granularité. En termes généraux, les objectifs de conception proposés par [Cochran et al. 2001] définissent les mêmes exigences de conception que celles abordées par la méthode proposée. Cependant, l'approche proposée fournit plus de détails techniques et spécifie le processus de conception en fonction des besoins du client.

Néanmoins, les exigences en termes de qualité, de délais et de résolution de problèmes définies par Cochran sont entièrement compatibles avec la méthode de conception proposée et peuvent être traitées par celle-ci. De plus, l'introduction d'autres exigences de conception liées à la sécurité des opérateurs enrichit le catalogue des exigences considérées par [Cochran et al. 2001]. La section suivante conclut le chapitre et le manuscrit en discutant les perspectives de ce projet de recherche sur la base des résultats obtenus et des applications possibles de la méthode.

6.3 Perspectives

Il est possible de classer les perspectives de recherche selon trois catégories principales : les perspectives générales, la collecte et l'analyse des données, et les extensions du modèle.

Comme point de départ, il serait intéressant de proposer le développement d'un outil logiciel capable de générer l'ensemble des configurations possibles de la solution finale du modèle de système sur la base des contraintes BF et techniques identifiées. Même s'il n'est pas encore possible d'automatiser entièrement la méthode, la phase de conception présente des éléments qui peuvent être traduits en un algorithme et être exécutés par un ordinateur. Par conséquent, elle peut aider l'équipe de conception à développer ses modèles de système après la phase de définition du cahier de charges.

L'intégration d'autres indicateurs clés de performance liés à la durabilité ou à l'optimisation de la production peut également constituer une perspective intéressante pour la méthode. Cette intégration peut se faire de manière similaire à l'intégration de la sécurité présentée au chapitre 5 en exploitant la flexibilité que procure l'activité de raisonnement de conception d'Évaluer et d'Optimiser à chaque étape du processus. Cette approche élargirait le champ d'application de la méthode et ouvrirait la voie à l'intégration d'autres méthodes ou outils dans le cadre du processus de conception. Cela amène le deuxième point de vue, qui est la collecte et l'analyse des données.

La méthode de conception proposée fournit une solution générale au développement d'un projet de conception et a été testée dans un cas d'étude. Cependant, il est nécessaire de déterminer comment elle est appliquée par différentes équipes de conception pour identifier sa corrélation avec les besoins de l'utilisateur. À cet égard, il serait avantageux de suivre un ou plusieurs projets de développement du début à la fin afin de recueillir des observations et des données pour une utilisation future.

Plusieurs options existent en termes d'extension du modèle, en fonction des données disponibles et des besoins des utilisateurs. Il serait intéressant d'étendre les activités de raisonnement de conception aux deux autres phases de la méthode proposée. Même si l'application des phases de conception détaillée et d'évaluation de la fabrication est assez simple avec les méthodes actuelles, cela peut être une forme de normalisation de la méthodologie de conception en utilisant des éléments communs entre les différentes phases.

English version

Chapter 1: Introduction and overview

Abstract

This chapter presents the thesis's main topics by introducing the first phases of research conducted on production systems design and safety integration. The study indicates that new production systems have to meet multiple constraints. Combining heterogeneous design practices and the multiplication of those constraints (also heterogeneous) greatly complexifies these systems' development projects. Indeed, considering all the constraints currently implies questioning decisions at all stages of the design process, which does not allow the project's objectives to be met in terms of cost, time, and performance. Therefore, the main goal is to integrate these constraints as early as possible in the system design process to make decisions more robust and prevent the project's objectives from not being accomplished or altered in the process. That integration work must imperatively rely on a generic framework that guarantees its deployment whatever the production system to be designed and whatever the nature and number of constraints to be met. This manuscript proposes a methodological framework for production systems design capable of considering design objectives in terms of cost, time, and performance, as well as integrating design decision-making expertise for safety aspects. Additionally, the validation of the proposal is made through a case study of an actual welding workstation part of a production system from a factory in the region. The case study is part of the Industrial Chair project in which this thesis has been developed. Finally, the chapter highlights the principal contributions and shortcomings of the performed research work, and it concludes with the thesis outline.

7. Problem definition

New processes, systems, and machines are being developed to improve the production rate and responsiveness of manufacturing processes. A substantial quantity of research is being conducted on advanced manufacturing processes [Qu et al. 2019], adaptive and intelligent manufacturing systems [Alcácer & Cruz-Machado 2019], digital and resource-efficient factories [Fröhlich & Halbartschlager 2019], collaborative and mobile enterprises [Henzel & Herzwurm 2018], and human-centered manufacturing [Åkerman & Fast-Berglund 2017], which are critical elements for developing a sustainable industry for the days to come. These contributions need to be aligned with the required system performance and the fluctuant industrial conditions. The market has a significant influence on product development [Aksoy 2017]. In the constantly changing balance between offer and demand, industries must adapt their products to clients' needs innovatively and efficiently to appeal to more customers and increase profit. From this point of view, the design team has a complex task in its hands because the production system has to meet technical requirements as well as market and safety requirements.

Designing a production system is a multi-step process that aims to satisfy a need by considering the available resources and constraints applicable to the project. One of the main tasks of the design team is to identify the real needs that the system must meet to be able to propose technical solutions capable of fulfilling those requirements. From this definition, several approaches have been developed in the design departments to adapt the steps to follow to the specific applications of each product (aeronautics, automotive, industrial, general consumption products) [Le Masson et al. 2017]. That has contributed to the diversification of the design theories and methods facilitating the area's development but has also created uneven practices that are not compatible and do not allow the integration of other requirements such as sustainability or human safety during design.

At the same time, for many years, the use of machinery in the industry has been regulated to meet safety standards and protect users. There are just as many safety measures as well as ergonomic measures aiming to protect workers in the short and long term. Too many accidents at work and ergonomic problems are observed on workstations. Indeed, in France in 2019, based on the data collected by the Social Security, the number of work-related injuries increased by a 0.6% compared to 2018 (655715 claims recognized in 2019 after a 2.9% increase in 2018). Also, the number of occupational diseases increased by 1.7% for the second year in a row compared to 2018, with 50392 recognized cases. Musculoskeletal disorders are the cause of 88% of them. In the United States in 2019, according to the Department of Labor, private industry employers reported 2.8 million nonfatal workplace injuries and illnesses, and there were 5333 fatal work injuries recorded, a 2 percent increase from the 5250 in 2018. That increase of work-related accidents and diseases in industrial environments calls for the consideration of safety risks during the design of any system involving human workers.

To summarize, in the current industrial context, multiple requirements need to be considered during the early stages of the design process to cope with the client and market needs. However, the current design theories and methods do not provide the necessary flexibility to integrate into a general framework all those requirements. The following section provides the identification of the main scientific issues identified for this research project.

8. Scientific issues

Based on the observation discussed in the previous section, and considering the heterogeneity and, most of the time, non-compatibility of industrial practices, the goal is to present a multi-criteria design framework to design complex, multi-technology production systems to meet design requirements, and flexible enough to integrate key performance indicators (KPI) such as human safety or sustainability. In this work, safety requirements are used as the decision-making criteria to exemplify integration in the design process. The following question summarizes the objective of the research work:

How to design a production system that integrates workers' safety while respecting the requirements regarding the design process, system model, and design reasoning?

In order to answer this question, three scientific issues have been defined:

- Issue 1: How to define a design framework to consistently manage the design process, system modeling, and design reasoning?
- Issue 2: How to define a methodology for analyzing the risks related to the safety of the production system workers?
- Issue 3: How to establish a connection between design data and risk analysis tools to consider the safety of operators as early as possible in the design of production systems?

From these three questions, the scientific issues can be divided into three main sections: design methodology, safety risk identification, and safety integration in design. The first two aspects require separated analysis, but they need to be compatible for the third aspect to be feasible.

The first issue focuses on the different elements of the design theories and methods. It is necessary to explore and analyze the different design approaches to identify their application ranges and define the different design phases, activities, and models. Those elements need to provide enough flexibility to allow the integration of different decision-making tools.

The second issue aims to define a generic risk analysis tool capable of considering the impact of an industrial environment on human safety. The purpose is to provide an approach for risk identification that can be applied in the early stages of the design process of a production system. In this question, the compatibility of the risk and design approaches needs to be considered in more detail.

Lastly, the main objective of the thesis is set in the third issue. The integration of risk analysis and production systems design demands a general framework that provides flexibility in the design process and robustness for the final solution.

9. Approaches and tools

In order to meet industrial requirements during design, it is essential to manage multiple elements: product representations, organization of the project, technical knowledge, and available resources. Based on those elements, this study has chosen to adopt a three-axial analysis perspective that is directly linked to the different theories and approaches of design found in the literature. These theories will be classified in terms of project, product, and design reasoning.

In the literature, most approaches seek to provide designers with methodological tools applicable to general product design cases based on different design process points of view. Some authors propose approaches centered in the project by giving structured, organized and sequential steps to be followed by the designer. In those approaches, the design team is at the center of the project, and the task is to define what to do but always following the same sequential steps. However, sometimes the tasks within the process are not explicitly described, giving the design team a certain liberty that can be advantageous or disadvantageous depending on the design problem. The product characteristics and properties are addressed in a very traditional way that is not always compatible with other approaches with higher levels of abstraction regarding the product modeling [Pahl et al. 2007] [Bonjour et al. 2003]. The performance of the final result is evaluated according to the effectiveness of the project; if the process has been rigorously followed, the final solution should meet the initial needs.

Other authors propose design approaches that define the design process around the product model. These methods focus on the product's life cycle and its interaction with the environment [Suh 2001] [Gero & Kannengiesser 2004]. However, the structure of the process is not as well developed as in other approaches. The performance of the final product is evaluated exclusively from the effectiveness of the solution to meet the needs of the customer; that is to say, that if the designer was able to extract the correct information about its main functions and its behavior, the product should be, in theory, capable of accomplishing its mission. Here, the designer's role in setting the goal is crucial because it is from this information that the product will be designed.

The third group of design approaches relies on the designer's activities, where consecutive steps of synthesis and analysis are applied to converge in characteristics and properties of the final product [Weber 2009]. These approaches better describe the designer's role and consider certain aspects from the product point of view. Also, mixed approaches take up some elements from the others and integrate them to offer a complete product-project process [Antony & Coronado 2002].

All the approaches mentioned above refer to the object of study as a product. In this research work, the study object is defined as a system seen as a set of components that interact with each other and perform predetermined functions to achieve a specific goal. Those components are distributed in different subsystems. A product, on the other hand, is seen as a single component conformed by individual parts.

Regarding safety integration, many authors have studied design theory to enrich it with other aspects relevant in the industrial context. The contributions of design theories and tools considering health and safety are detailed by [Sadeghi et al. 2016]. However, it is relevant to note that these methods and tools are applied only under specific conditions, and their integration into the design process is, most of the time, limited considering the current approaches.

The standard [EN ISO 12100 2010] provides a diagram representing the risk reduction process from the designer's point of view. The standard also provides an iterative approach to the process that distinguishes several steps needed to minimize the residual risk. This process can be burdensome to apply as described in the standard because it is iterative and time-consuming, requiring skills that design teams do not necessarily have.

In this standard, classification criteria are given for risk assessment and then risk reduction. Logically, it is evident on the one hand the criteria related to the risk factors and, on the other hand, those related to the reduction of the risk. The designer has the double task of detecting the sources of risk in the design of the machine and finding solutions to reduce these risks.

All the approaches and tools mentioned in this section are explained in detail in chapter 2. The introduction of those concepts is necessary to position the work in the research area and understand the expected contributions and boundaries of the thesis, which are presented in the following section.

10. Research methodology

As has been exposed in the previous sections, the objective of the thesis is to propose a design method for production systems that considers the industrial requirements of the final solution. Accordingly, the basis of the thesis can be identified in Figure 1.1. The design science bubble represents the three main elements of product design: design process, product model, and design reasoning activities.

According to [Haik et al. 2015] the design process is a decision-making procedure (often iterative) in which the basic sciences, mathematics, and engineering sciences are applied to convert resources to meet a stated objective optimally. Regarding product modeling, [Geryville et al. 2007] determine that the product's architecture is defined not only by the decomposition of the final product into components, functions, or behaviors but also by the interactions between all components. [Do & Gross 1996] states that the design reasoning activities correspond to the problem-solving mental processes of designers, such as analysis, synthesis, and evaluation which are fundamental during any design problem. Those three elements interact and affect each other to give form to the design solution. The interactions between the design process and the product model can be considered bidirectional in the sense that the definition of the product determines the different design phases of the process, but at the same time, those phases define its characteristics. The interactions between the product model and the design reasoning activities are not direct because these activities act as the guidelines needed in the design phases to define product characteristics.

On the key performance indicator (KPI) bubble appear the different indicators that could be integrated into the design method to respond to the industrial requirements. In this work, safety is the indicator to be integrated into the process to validate the flexibility and adaptability of the design method. Figure 1 will appear in different parts of the manuscript to show the elements developed in the different chapters.

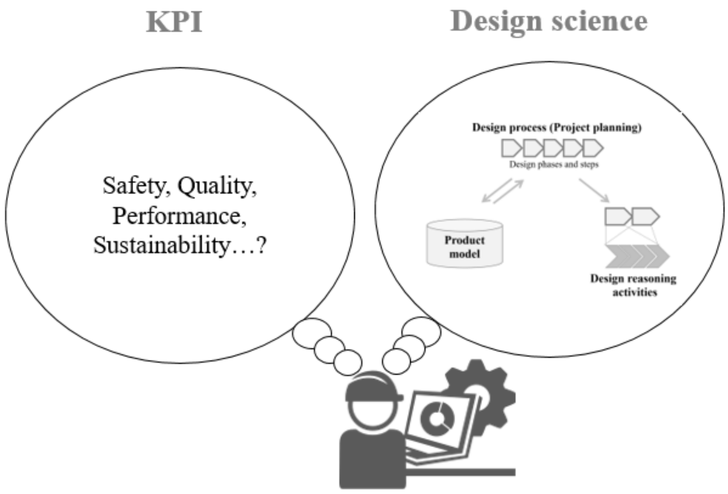

Figure 1.1 Principal elements of the thesis.

Considering all the previous, the research methodology has been divided into five parts:

Part 1: Overview of the main concepts of design theories and methods, risk identification, and assumptions of their integration.

Part 2: Development of a general production system design framework based on the findings in previous research projects.

Part 3: Development of a risk analysis tool based on safety parameters compatible with the proposed general framework and based on the safety elements retained during part 1.

Part 4: Integration of the risk analysis tool into the general design framework. Explicit representation of their common elements and interactions.

Part 5: Application of the design method on a case study. This part is presented as the last one, but it was developed in parallel with the development of the other four parts.

The study identifies and analyzes theories and methods that partially or entirely answer the related scientific issue. State of the art is defined as the result of the insight into the framework and methodology description. The second step is to define the structural elements of the method. The main ideas of the thesis are elaborated and demonstrated in this step. That is followed by the development of the risk analysis tool. The development details are given here. The fourth section presents the integration of risk identification into the design process. Finally, in part five, an example is given to validate each component of the method.

11. Case study

A case study of a welding workstation from a preexisting production system (Figure 1.2) will be used to test the coherence of the different elements of the proposed methodology. This example's primary focus is the logical sequencing of study objects to show how the concepts are applied in the method. The workstation is divided into two zones, one for welding and one for feeding. The feeding zone is where the worker charges the unwelded parts to feed the welding zone and discharges the welded parts. In the welding zone, the robot welds the parts fed by the worker. The two zones are connected by a rotary table that exchanges parts between the two areas.

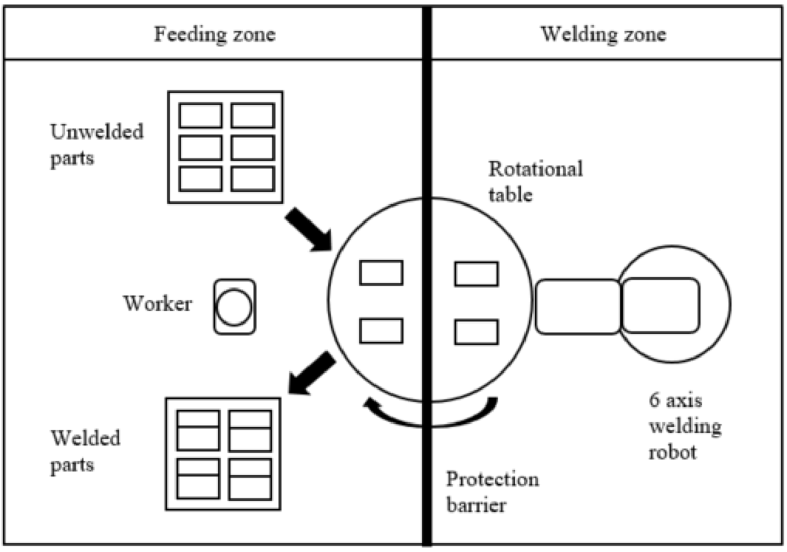

Figure 1.2 Distribution of the welding workstation.

12. Expected contributions of the thesis

This section gives an overview of the expected general contributions of the thesis. Detailed contributions on specific solutions are discussed in the relevant chapters. The contributions of the thesis can be listed in three categories: contributions related to the general design framework structure for production systems, the energy-based product model, and the integration of KPIs into the industrial design independently of the nature of the indicator.

The first contribution is a methodological framework for designing production systems based on system engineering concepts with the integration of operator safety approaches and operational reliability from the elicitation phases of the requirements. The proposed structure of the framework should contribute to the scientific community by providing a design process that allows the traceability of every decision made by structuring the mental design reasoning of the designer. The confrontation between the existing design approaches and the actual design conditions of a production system within the industry exposes the lack of a more detailed step-by-step approach to overcome the potential obstacles that might appear during the process. The proposed method defines those missing steps to achieve a successful design project development.

The second contribution relies on the proposal of a product model based on the energetic interactions and treatments that occur inside a production system. This approach identifies the critical elements to transition from the functional architecture to the organic architecture of the system, which has been proven to be one of the most problematic steps of the design process. It is expected that the product model will be flexible enough to be applied in large production systems and support different scenario analyses.

Subsequently, the last contribution is supported by the integration of the two previous aforementioned. The integration of a KPI into the proposed design framework is made through the flexibility of the energy-based product model. For this work, safety indicators have been used as the primary approach due to the development of new industrial methods that might affect human safety. However, it is only one of the many approaches that can be included and adapted to the design framework, such as sustainability or productivity. Other research projects have explored the integration of specific indicators into design, but not in a generic way where the approach can be interchanged without changing the general framework. That interchangeability gives the design framework the possibility to be adapted and respond to the client's needs without significant changes.

13. Structure of the thesis

The thesis outline is based on the research methodology, but it is not divided accordingly due to the links between some of the elements presented in each chapter. Based on that, the structure of the thesis is as follows:

Chapter 1 presents the problematic of the thesis and identifies its principal scientific issues. A brief introduction of the principal approaches and tools found in the literature is presented to position the research accordingly. The research methodology is explained, and the main expected contributions of the thesis are listed.

Chapter 2 presents a literature review on production systems design, safety assessment tools, and human factors related to workers' safety in working situations. This chapter details all the elements introduced in chapter 1. Analyses and compares the different design approaches and evaluates their compatibility with the risk assessment tools.

Chapter 3 introduces the first two elements of the proposed design framework: design process and design reasoning. Those elements act as the structure of the design method providing specific and sequential steps to follow the development of the final solution.

Chapter 4 presents an energy-based model for the system based on elements from Goal-Function-Behavior-Structure (GFBS) and the proposed Behavior-Energy-Structure (BES).

Chapter 5 shows how the first two phases of the method are applied to a welding workstation study case. This chapter also explains safety integration because the risk identification tool uses the BES model to analyze possibly dangerous situations.

Chapter 6 presents the conclusions and perspectives of this research work. This chapter contains both a general conclusion and one focused on the application of the method. It also emphasizes the general limitations of the approach and strategies for overcoming them. Finally, the thesis ends with a discussion of the project perspectives.

Chapter 2: Literature review

Abstract

This chapter presents an overview of the theories, methods, tools, and techniques proposed in the literature related to human safety and a production system's design process. Different design approaches have been explored to identify common elements, deficiencies, and strengths to be used as part of a complete design framework compatible with human factors and safety assessment. On a second time, the literature review will focus specifically on the integration of human factors during design, aiming to review and point out the required information for an early safety assessment for production systems design. The objective is to show the different approaches proposed in the literature about safety assessment and human factors identification in production systems. New methods, systems, and machines are being developed to improve the production rate and reactivity of manufacturing processes. Those contributions need to be aligned with cost, time and performance efficiency, and worker's safety in this respect. In this broad framework, the principal focus of the thesis is worker's safety inside a continuously changing environment. So it is important to understand the main differences between current and future manufacturing systems from a human-centered perspective. Also, the widely discussed risk detection topic is boarded on the different approaches present in the literature to have a solid base for its integration on design. Finally, the chapter presents the literature review analysis and explains the principal elements to consider for the proposed method.

1. Introduction

In terms of design theories and methods, numerous approaches have been proposed for general products. However, it is essential to note that even if they are generally used for individual products, it is also possible to apply them for systems design. As explained in Chapter 1, In this research project, the main focus is the design of production systems, so it is important to make the difference with the study objects used in the literature (products). The use of the system as a study object means considering organizational and life-cycle aspects that differ from the ones considered for a single product, such as production scheduling changes or the phase of installation. The level of detail considered for a system varies extensively considered to a single product. In a system, the product can be considered one of the system's basic components that perform a given function without considering its individual parts.

As mention in the previous chapter, human factors are closely linked to the performance of a production system. How workers behave in a production system impacts production parameters and the occurrence of dangerous situations. The working situation concept is defined as the set of all production system components and human workers performing one or more tasks through interactions to achieve a predefined objective under predefined working conditions [Hasan et al. 2003]. A risk exists when a worker is exposed to one or more phenomena capable of causing damage in that working situation. That is one of the main reasons why the working situation's information must be considered during the design process.

Talking about the task of design, it is possible to say that a design project is composed of a structural dimension in the form of a framework, an organizational dimension in the form of a development schedule, a morphological dimension in the form of a system model for the development of the final solution, and an analytical dimension in the form of problem-solving activities. As shown in Figure 2.1, from a general viewpoint, those elements are the project planning which is determined by the design process as a set of organized phases, the product model, which records the evolution of the product design from the client's needs to the final solution, and the design reasoning activities which influence the actions to be taken to achieve the intermediate design objectives.

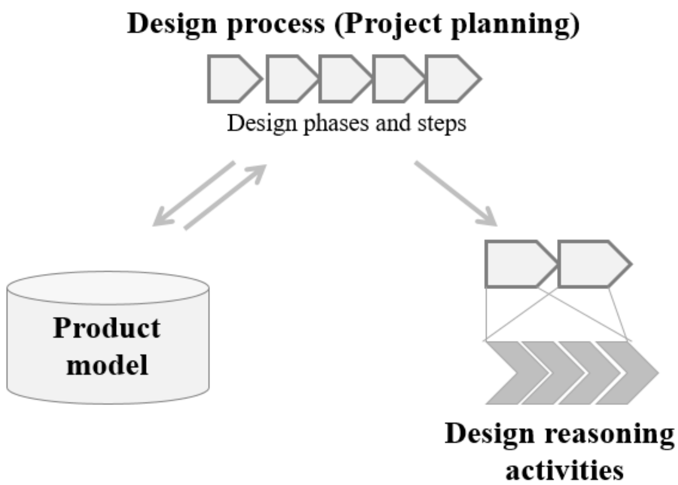

Figure 2.1 Design framework elements.

The interaction between the design phases and the product model is bidirectional, which means both impact and define each other along the design process. Those design phases dictate the definition of certain characteristics of the product at a specific step, and at the same time, the information obtained for the product model becomes the input for the following design phases. Going into more detail, multiple aspects compose a design method, the most common have been described by [Lutters et al. 2014] and divided into two categories: the first group provides the aspects that arise from the design project in which a design method is utilized, while the second group renders the qualities that are inherent to the method itself.

1.1 Project-related considerations

In this subsection are discussed the project-related elements that are common to every design project. These elements define the design problem and the general perimeter of the expected results. Also, they are considered for the definition of this research project proposed method, specifically during the clarification of the design task in Chapters 3 and 4.

- Objective: The purpose of employing a method in which restrictions, functionality, complexity, and the desired output all play essential roles [Munksgaard et al. 2012; Olsen et al. 2008] is the desired added value. Furthermore, the real value-added must justify the money, time, and effort spent using the method. Unfortunately, this compromise is frequently overlooked, resulting in the everyday use of a standard set of tools/techniques [Hubka & Eder 2012]. Making the objective clear by identifying the desired final state of employing a method provides organization, transparency, and critical evaluation of method implementations and outcomes.

- Phase: The available initial state varies greatly depending on the phase in which a method is used. For example, the term strength analysis has distinct connotations in conceptual design than it does in detail design [Lutters et al. 2014]. The phasing refers to the accuracy, completeness, and quality of the available data, as well as the quality and level of detail of the expected outcome. Furthermore, the amount of time and effort devoted to employing a method is usually determined by the phase, which necessitates a balance between the outcome's reliability and the resources expended.

- Team composition: The design team composition can have a significant impact on the project's overall success [Kreimeyer et al. 2007; Reiter-Palmon et al. 2012; Zhang & Zhang 2013]. That refers to the type and level of knowledge available, as well as the team's overall size. In a project, the role of tools/techniques must be assimilated as follows: The team composition influences whether tools/techniques are used to provide in-depth knowledge or to enable communication and information sharing within the team [Rauniar & Rawski 2012]. They can also either supplement team expertise or allow for the underpinning and strengthening of current skills and experience.

- Constraints: No matter how useful and successful a method is, it will rarely be feasible to utilize its capabilities completely. The freedom to operate is limited, as it is with other occupations that require time or money inputs [Volkmann & Westkämper 2013]. In other words, the use of a tool or technique is limited by the amount of time available, which is decided by the available lead-time or the amount of time allocated. There are limitations based on the available resources (which can range from people to hardware). Furthermore, the type and quantity of risk (technical or commercial) involved will almost definitely impose limits on how a method is chosen, applied, contextualized, as well as how the outcomes are integrated into the overall project.

- Complexity: Even simple product development projects can be complicated due to the involvement of external organizations such as legal experts, approval agencies, or independent testing facilities.

The quantity of variables (complexity), the time-dependency of those variables (dynamics), the (in)visibility of a subset of the variables (opacity), and the fact that variables might be connected are all factors that influence the complexity of using a method (dependency). Next to this, the most significant contributor to a project's complexity may be attempting to meet many, often contradictory goals simultaneously [Du Preez et al. 2009].

- Strategic contribution: A method is frequently used in multiple projects. As a result, its application is oriented toward the ‘average' project. Furthermore, those other initiatives, as well as the company strategy, may skew the implementation and experience. On the other hand, applying a method in a single project may contribute to an organization's strategy and experience.

1.2 Inherent aspects of the method

In this subsection are discussed the inherent aspects of a design method. The elements presented here are common for the different design methods in the literature, but their representation and interpretation during the design process are different for the different approaches. These elements are considered for the definition of the proposed method during task clarification and conceptual design and are part of the discussions in Chapters 3, 4, and 5.

- Initial state: Every method requires a specific input; if this input is not available, its use is pointless, or the results will be partial or untrustworthy. This input can refer to the type or amount of information necessary, the quality of the information, as well as the method prerequisites (which might range from hardware to training). The suitability of the start state is mainly determined by experience because achieving a feasibility study on whether and how the intended final state can be achieved is reliant not only on the method but also on the product under development and the project's status and evolution. As a result, the alignment between the initial state and the project progress determines the relationship between the project and the method. The project takes the lead more often than not, whereas it would be more effective to set clear limitations on development from the start state, which is essential to begin using critical tools/techniques.

- Final state: Using a method in a design cycle is justified if the result contributes adequately to the product definition, better underpins the product definition or completes the definition. As a result, the D-state serves as a link between the initial and final states. A requirement specification for the method used might be portrayed as the desired or required final state. The processes involved can start from either side, depending on the sort of method: in the instance of a brainstorm, the start state is clear, and the different results can only be imagined, leading to an ‘open' process, in which the course of action is the means of control. At other times (for example, for finite element studies), the output is well defined, resulting in a ‘closed' process that may be regulated by the output's reliability.

- Functionality: A tool's or technique's use is justified by its purpose. In a way, functionality dictates the D-state between the initial and final states and causes or aids the design cycle's evolution [Lutters et al. 2004]. In many circumstances, however, the requested functionality and the functionality offered will be incompatible. As a result, using an existing method may result in a compromise in the functionality that is required. Furthermore, the functionality provided in the 'set' of tools/techniques will bias working practices and even design trajectories.

- Alternatives (equipment): Other tools/techniques may demand more advanced means of execution, even if the equipment needs are not more than paper and pencil. Some software applications place many restrictions on things like processor power and storage capacity. Furthermore, Virtual (or Augmented) Reality tools may rely on the availability of a wide range of highly specialized hardware [Becker et al. 2005; Nee et al. 2012] (e.g., haptic devices [Grane & Bengtsson 2013; Van Houten & Kimura 2000] or even caves [148]); while more flexible, the use of synthetic environments [Lutters & Van Houten 2013; Miedema et al. 2009] nevertheless necessitates careful thought. That means that equipment is not just an out-of-pocket expense when employing a tool or technique; there are two more factors to consider. To begin with, the effectiveness and efficiency of employing a method are closely tied to the equipment used; so, choosing an equipment alternative may have a non-linear impact on the quality of the product. Second, for expensive equipment, the selection of tools/techniques across several projects can have a strategic impact: equipment may be implemented in response to many requests, but equipment availability may bias method selection and use.

- Cost: The direct cost of employing a tool or technique includes labor, equipment, and consumables. Indirect expenses include equipment availability, licensing, and (developing) expertise in using the method/equipment combo. Although it is difficult to account for cost estimates for a single project, indirect costs typically outnumber direct expenses by a large margin. Employing a method may appear to be cost-effective from this perspective, but having the method readily available may result in hidden costs that are not obvious in a single project.

- Time to execute: While determining the time required to execute a method is typically quite simple, determining the time that can or should be dedicated to the same execution is far more challenging. That has to do with the amount of time available (deadlines), the cost of using the equipment for a set period, and, most importantly, the frequently non-linear relationship between the amount of time invested and the quality of the product received. Furthermore, the accuracy of time spent estimations vary greatly. The time required for finite element analysis, for example, may be predicted quite reliably, whereas the time required for a focused brainstorming session can be less precise.

- Time to implement: As previously stated, a given project will focus on using a method, and any effort linked to making that method available will be considered additional work or a supra project (i.e., tactical or strategic) activity. That implies that a company's proper integration of a method may necessitate more strategic commitment than can be justified by a single project. As a result, such implementation paths may impose significant overhead on all projects concerned. Depending on the company goal, this may result in a pragmatic approach in a single project, causing a tool or methodology to be underutilized. To give an example, many methods exist for transferring project findings to following projects; nevertheless, despite the fact that doing so would be strategic, few project leaders promote spending time recording, formalizing, and analyzing project results and experiences.

- Installation time: Unlike the implementation time, which is concerned with making a method capability available, the installation time is concerned with the time and effort required to set up the environment so that the method can be used effectively. Again, this may appear futile for a brainstorming session (although getting all required stakeholders in the same room can be difficult enough; with technological solutions, this may be easier [Damgrave & Lutters 2013], but installation will take longer), but configuring a Virtual or Augmented Reality environment or a Synthetic Environment for a specific project most certainly requires considerable effort [Miedema 2010; Bernard & Xu 2009]. When compared to production environments, even if the equipment is accessible, process planning, production planning, and set-uptimes need a significant amount of energy.

- Stakeholders are those who have an interest in something. Only when the right set of stakeholders are present can tools/techniques be fully utilized. Much of the logic in this regard is self-evident, but there are numerous traps to be avoided when employing tools/techniques to include (end) users in the design process [Miaskiewicz & Kozar 2011, Moffat 1998]. Integrating the proper sort and number of stakeholders is also challenging to establish need specifications [Miedema et al. 2007] and decision-making [Dankers 2013].

- Professionalism: The capacities of the stakeholders are important in addition to the type and amount of stakeholders. Even although certain approaches have their qualifications or certifications (C2C [Luther 2012], TRIZ [Ilevbare et al. 2013], Lean six-sigma [Swink & Jacobs 2012]), any tool or process requires trained operators. In this regard, there are two types of abilities: organizational and content-related. Being able to drive a car is not the same as understanding how a car works. To put it another way, the tool's value must be understood independently of its use in design cycles. Another factor becomes relevant when (end) users are included as stakeholders: the more an (end) user is involved in the process, the more they will grasp the design cycle itself. As the ‘casual' user develops into a ‘trained' user, the associated prejudice may obstruct the process. In this situation, stakeholder expertise may have an explicit upper limit for (end) users, but other stakeholders may have an implicit goal of increasing their expertise.

- Training: A stakeholder's level of knowledge is closely tied to their experience with (particular) tools/techniques. The majority of the time, this experience is gained while using the method. Formal instruction usually provides a clear start, but simple familiarization occurs when the shoulder is placed on the steering wheel. As a result, the effectiveness and efficiency of using tools/techniques can vary greatly depending on the stakeholders. As a result, training level scan has a considerable impact on installation time, execution time, final state, and, as a result, cost. The certification mentioned is used to assess the training level to avoid having a detrimental impact on the method itself. However, the required amount of training and the impact of the training level is unclear for the vast majority of instruments. Simultaneously, there is a propensity to regard tools/techniques as infallible and certain solution suppliers rather than resources in the hands of artisans. Regardless of how valid this approach is, it deviates significantly from the actual design cycle.

- Quality: Because quality can be both objective and subjective [Pirsig 1992], the many perspectives shown prevent any definitive statement about using a method. The impact and meaning of a method differ depending on whether it is used for a single project, a corporation, or a (group of) people. At first glance, this appears to make the aspect quality impractical. It can also be thought of as the connecting pin between distinct points of view, i.e., the component that connects strategic attention to the operational application.

In the following sections, a general introduction of the design theories and approaches found in the literature is made. The elements cited in the introduction of this chapter can be found in the different design theories and approaches as constituent elements. Some of those elements and the applications proposed by the different authors will be analyzed to enrich the definition of the proposed method of this research work.

2. Design theories and approaches

It is important to clarify that most of the design theories and methods described in this chapter have been conceived for designing individual products but can also be applied for production systems design which is the main focus of this study. The interest is to describe the main phases of designing a production system for a specific product. This clarification is required to differentiate three fundamental concepts involved in industrial manufacturing: product, system, and production system. A product is the compound of numerous elementary parts such as screws, metal sheets, or cylinders. Now, a system is the union of different products to develop a specific task. For example, it is possible to say that an engine is a product and the car is a system. On the other hand, the production system is the compound of structures, machines, and processes required to produce this product (Figure 2.2).

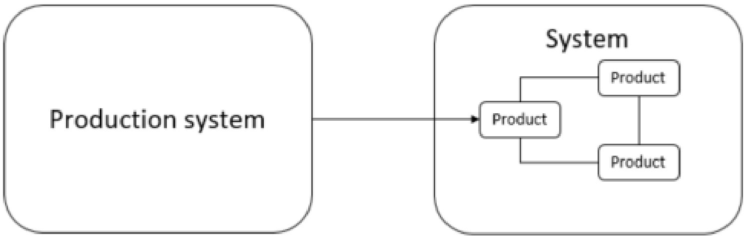

Figure 2.2 Product, system and production system interactions.

In terms of design, this chapter aims to mention the most representative design methods and theories of every approach, giving a general idea of every process's steps and main stages. A comparative analysis has been carried by [Scaravetti 2004] between the different approaches of design processes proposed in the literature. That comparison aims to find the common elements of the studied design approaches and has been a starting point for this literature review. In the following subsections, the preponderant approaches are explained in more detail.

[French 1971]	Analysis of problem		Conceptual design		Embodiment of schemes		Detailing	
Problem Solving Technical System (Pahl & Beitz 1995)	Product planning and clarifying the task; Situation; Strategy – Needs & Trends; Ideas; Idea; Task – Problem, Function; Product proposal – Functions; Requirements list – Demands & Wishes	Specification of information	Conceptual design; Functions Structure – Overall Function, Sub-functions; Working Structures – Working Principles, Overall Solution; Principle Solution – Properties, Variants	Specification of principle; Concept	Embodiment design; Construction Solution – Preliminary layout, Definitive layout	Specification of layout	Detailing design; System structure – Individual parts; Production documents	Specification of production
QFD (Akao 1993)	Demanded quality; Quality elements		Functions; Quality characteristics; Mecanisms		Costs, Reliability		Basic components; Process; Equipments	
House of Quality (Prasad 1998)	Weighting factors; Strategic needs, Tactical needs, Operational needs; Customer requirements	Product planning	Quality characteristics				Parts deployment; Process planning; Production planning	
(Scaravetti 2004)	Analyse du besoin; Besoin; Cahier des Charges Marketing; Fonction globale; Critères de qualification; Liste d'Exigences	Cahier des Charges Fonctionnel	Approche Fonctionnelle – Fonctions structurantes; Principe de fonctionnement, Concept – Approche organique (OT détaillé), Approche physique (BDF – GSC); Concept de solution (WS)		Architecture; Configuration		Solution de Conception; Documentation Produit	
Axiomatic Design (Suh 2001)	Customer domain – Customer's needs; Functional domain – Functional requirements & Constraints		Design parameters	Physical domain			Process domain – Process variables	
Démarche LCPN (Aoussat 1998)	Traduction du besoin; Besoin identifié, Stratégie; Fonctions	Cahier des Charges fonctionnel	Interprétation du besoin; Définition du produit; Veille; Concepts directeurs	Cahier des charges concepteurs	Architecture		Produit-Process; Eléments indispensables, Eléments de conception, Composants et pièces; Process global, Process sous-ensemble; Equipement - Organisation, Fiabilité - Coûts	Dossier produit
Value Analysis (Miles 1972)	Analyse Fonctionnelle Externe/du Besoin; Objectifs globaux = besoins; Besoin fondamental; Fonctions de services, Fonctions contraintes; Arbre fonctionnel, Critères d'appréciations, Niveau performances	Cahier des Charges fonctionnel	Analyse Fonctionnelle Interne/Technique; Fonctions internes FAST; Solutions alternatives, Bloc Diagramme Fonctionnel; Solutions					
V-Model (IABG 1997)	Modèle fonctionnel; Attentes, Besoins clients; Fonctions; Performances fonctionnelles	Cahier des Charges *(fonctionnel)*	Modèle structurel; Modèle conceptuel – Contraintes, Paramètres de conception; Modèle approximé d'ingénierie – Performances estimées	Spécification technique du besoin		*Dossier de concept de produit*		*Dossier de Définition* – *Réponse STB – caract. prod. + procédés fab.*
Requirements Engineering (Glinz 2011)	Context; Project requirements – Goal, Scope; Customer Requirements Specification; Features; Requirements – Functional requirements, Non-functional req., Domain properties	System Requirements Specification	System – Specifications, Properties; *Machine, Software, Human*	Software Requirements Specification – *Machine Requirements Specification*	Configuration Release		Component Artifact – *Computers, Programs*; Process requirements	
GORE (Lamsweerde 2001)	Objectifs de haut niveau; Objectifs concrets, Contraintes; Hypothèses + Exigences; Obstacles; Functional requirements, Non-functional req.	System Requirements Specification	Spécifications fonctionnelles dynamiques, Spécifications fonctionnelles des informations, Attributs – Propriétés *(spéc. non-fonct.)*; *Machine, Software, Human*	Software Requirements Specification				
System Engineering (Faisandier 2011)	Domaine de Spécification; Finalité, Mission, Objectifs, Besoin & Attentes; Cahier des Charges	Spécification Technique	Architecture fonctionnelle et comportementale; Architecture organique, Connexions physiques, Interfaces fonctionnelles	Dossier de Conception	Domaine de la Conception	Dossier Justificatif		

Figure 2.3 Concepts used in Various Conceptual Design Methods across Engineering [Scaravetti 2004]

2.1 Project planning and design process approaches

The methodologies based on the project planning and design process provide the designer with organized, structured, and sequential steps (Figure 2.4). That is the case of Systematic Design proposed by [Pahl & Beitz 1996, Pahl et al. 2007], which describes engineering design as a sequence of four phases: Task clarification, conceptual design, embodiment design, and detailed design. Each of the four phases includes a sequence of activities carried out iteratively [Tate & Nordlund 1996, Unger & Eppinger 2011]. Another example of this group is Systems Engineering [Bonjour et al. 2003, De Weck et al. 2011], which is defined as a process of integration of all the disciplines involved in the life cycle of a system taking into account different needs in order to develop a solution that is economical, efficient and satisfying from all points of view. [Menand 2008, Messaadia 2008].

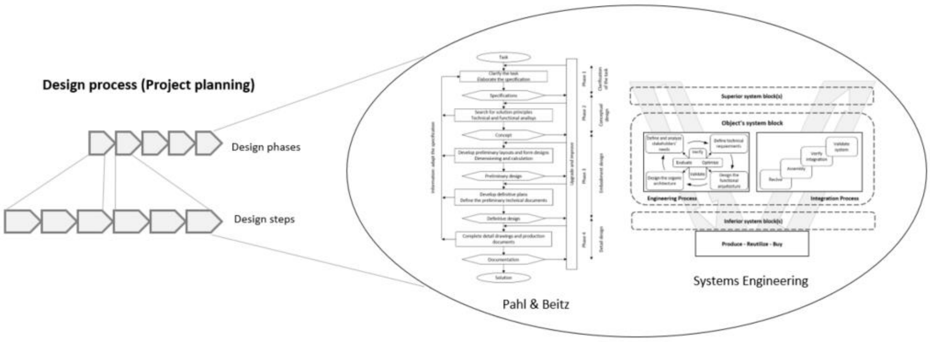

Figure 2.4 Project planning and design process approaches.

2.1.1 Systematic design

The systematic design was developed in the nineties by G. Pahl and W. Beitz. It is a generic design approach that relies on methods and tools commonly used by designers (see Figure 2.5). From a general view, this work makes important contributions to design activities in several areas. For example, the customer's needs are fully integrated into the design process, which helps control drifts against the product's performance goals [Pahl 1996].

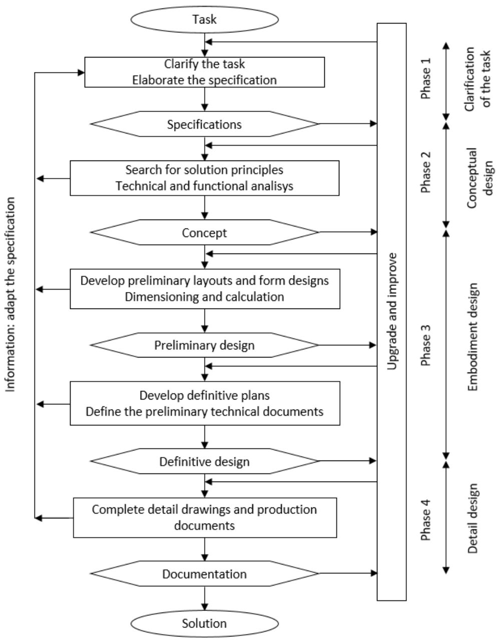

Figure 2.5 Design process proposed by G. Pahl and W. Beitz [Pahl 1996] [Djefel 2010].

The Systematic Approach of Pahl and Beitz characterizes engineering design as a four-phase process: (1) Task clarification, (2) Conceptual design, (3) Embodiment design, and (4) Detail design are the four steps in the design process. Collecting, creating, and documenting the requirements of the product to be designed is what task clarification is all about. The goal of conceptual design is to determine the fundamental principles and outline of a design solution (or concept). Embodiment Design then refines the design into a layout that meets a variety of technical and financial requirements. Detail Design is in charge of completing the design and preparing the production papers. Each of the four phases consists of a series of actions that can be completed in an iterative fashion.

After each phase, a 'decision-making step' is conducted to evaluate the phase's outcomes and determine whether the next phase can be started or if it needs to iterate. The lowest possible iteration loop is preferred here.' [Pahl et al. 2007, Pahl et al., Pahl et al., Pah Iterations between phases are not explicitly excluded by Pahl and Beitz. The approach's phase-based nature, on the other hand, supports a "waterfall" view in which iterations are limited to a single phase [Tate & Nordlund 1996, Unger & Eppinger 2011]. The phases of the systematic approach, as well as the activities connected with each phase, are shown in Table 2.1 (does not include iterations within and across stages).

Table 2.1. Pahl & Beitz systematic approach.

Phases	Activities
Task clarification	Define basic market demands Define attractiveness demands of the market segment Document customer-specific technical performance requirements Refine and extend the requirements using the checklist and scenario planning Determine demands and wishes
Conceptual design	Abstract to identify the essential problems Establish function structures: overall function – subfunctions Search for working principles that fulfill the subfunctions Combine working principles into working structures Select suitable combinations Firm up into principle solution variants Evaluate variants against technical and economic criteria
Embodiment design	Identify embodiment-determining requirements Produce scale drawings of spatial constraints Identify embodiment-determining main function carriers Develop preliminary layouts and form design for the remaining main function carriers Select suitable preliminary layouts Develop preliminary layouts and form designs for the remaining main function carriers Search for solutions to auxiliary functions Develop detailed layouts and form designs for the main function carriers ensuring compatibility with the auxiliary functions carriers Develop detailed layouts and form designs for the auxiliary function carriers and complete the overall layouts Evaluate against technical and economic criteria Optimize and complete form designs Check for errors and disturbing factors Prepare preliminary parts lists and production documents
Detail design	Finalize details; complete detail drawings Integrate into overall layout drawings, assembly drawings, and parts lists Complete production documents with production, assembly, transport, and operating instructions Check all documents for standards, completeness, and correctness

At a macroscopic level, this one is composed of four sequenced phases allowing to conceive a product entirely starting from the rough needs of the customer. Although this process is presented as sequenced steps, both authors emphasize that most of them require iterative and collaborative work. However, this detailed organization is left to the initiative of the designers.

2.1.2 Systems Engineering

According to AFNOR, system engineering is a "process of integration of all the disciplines involved in the life cycle of a system taking into account the different needs, in order to develop a solution that is economical, efficient and satisfying from all points of view" [Menand 2008] [Bonjour 2003] [Haskins et al. 2006].

In order to fully understand the scope of this design process, it is also important to define what a system is. According to AFNOR, it is "a composite set of personnel, hardware, software (or computer systems) and processes, organized so that their interoperability allows, in a given environment, to satisfy the needs and fulfill the missions corresponding to their purpose" [Menand 2008] [Messaadia 2008].

Although system engineering is based on a general design framework, it still offers a precise and potentially tooled process consisting of four steps (see Figure 2.6):

- Define the "needs" of "stakeholders."
- Define the technical "requirements."
- Design the "functional architecture" of the system.
- Design the "organic architecture" of the same system.

The proposed design process is represented by a "V-shaped cycle" (see Figure 2.6). The tip of the "V" includes all the stages of the system's physical design (which becomes a product). The downstream branch contains the four major steps, while the upstream branch is associated with the integration and validation steps of the elementary subsystems composing the system to be designed. Of course, the whole is constantly interacting through modification actions that guarantee the respect of the "needs" of the "client" and "stakeholders," but which also ensures the coherence of the whole throughout the project. System engineering does not intervene at this level [Fiorèse & Meinadier 2012]. It does not cover the entire design activity.

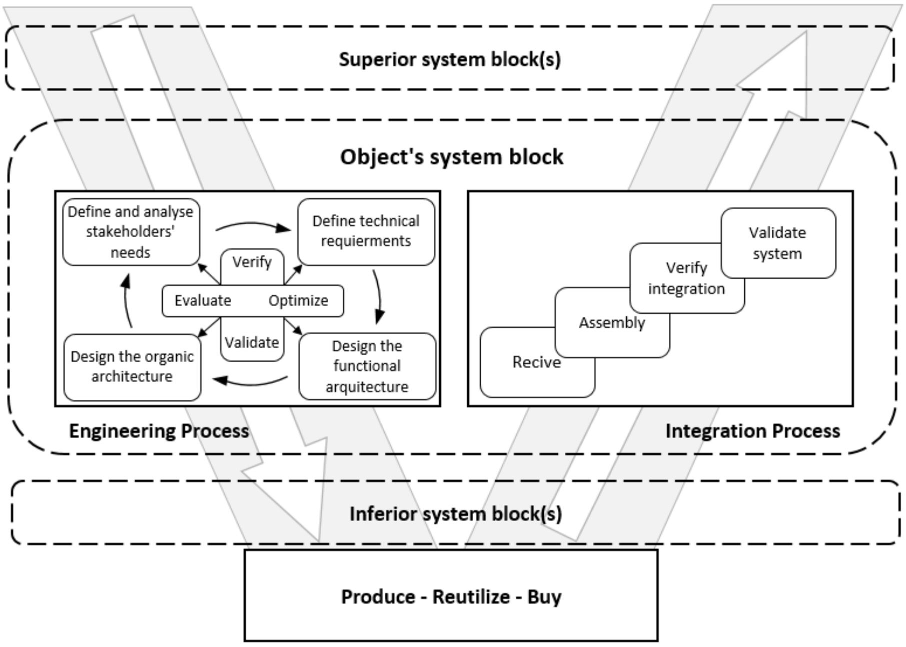

Figure 2.6 The "V" Design Cycle of System Engineering [Faisandier 2011].

The first step is to identify the customer's activity and what they want systematically. Therefore, it includes the "owner" and all the users who interact with the system to design. Their needs are first identified and transcribed in their business language. The second step translates these needs into requirements in the designer's language (called "prime contractor"). "These requirements are the clarified expression of a need presented in a formal language (computer, graphic, mathematical, ...) or natural. They must be realizable and verifiable "[Faisandier 2011] [Fiorèse & Meinadier 2012].

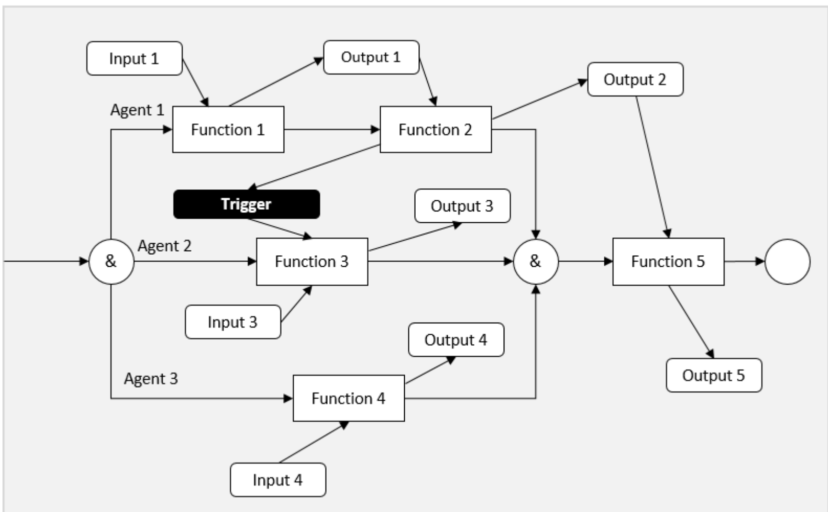

Figure 2.7 Example of functional architecture (language "effbd") [Faisandier 2011].

The third step is to propose and structure functional solutions (see Figure 2.7). Each can be dimensioned and evaluated from specific modeling tools that allow in particular to address the static aspects, dynamics, and all the interactions between the system functions. Therefore, functional architecture is a set of elementary functional blocks and functional links whose behavior is well known. It can be decomposed into several levels [Fiorèse & Meinadier 2012] [Lebrun & Mare 2009] [Mare 2009].

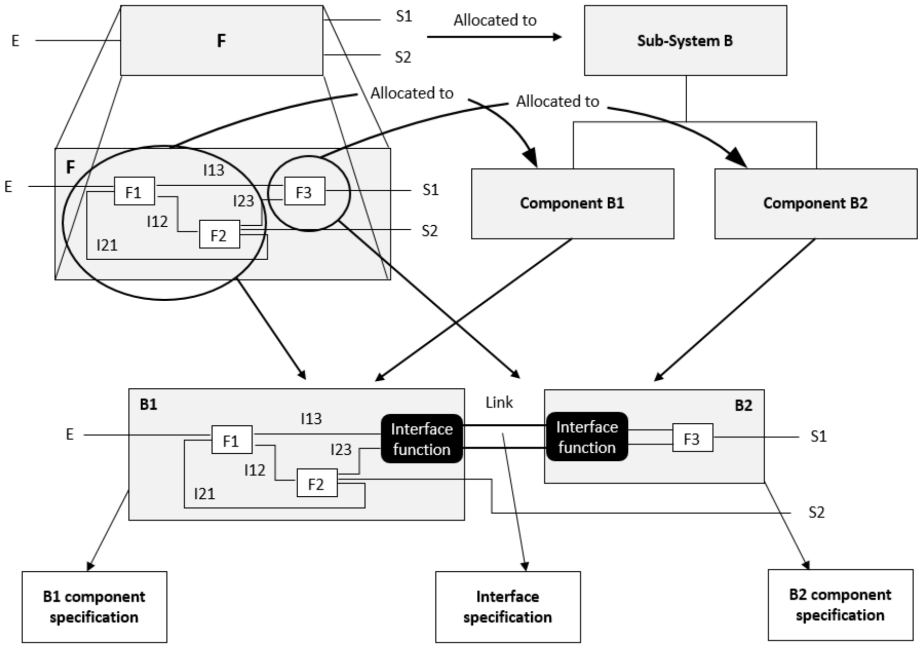

Figure 2.8 Example of organic system architecture construction [Faisandier 2011].

The fourth and final step breaks down the initial system into elementary subsystems (see Figure 2.8). It can also have multiple levels. This decomposition is based on the previously created functional architecture. Therefore, an elementary subsystem is a grouping of elementary functional blocks, internal and external functional links. These translate the interactions with other subsystems. It should be noted that the same functional architecture can make it possible to build a multitude of different organic architectures. The choice of this one depends essentially on the "needs" of the "stakeholders." For example, it can result in the implementation of a modular strategy that makes it possible to obtain diversified products from standard elements [Fiorèse & Meinadier 2012].

With the increasing complexity of the systems considered, in particular, obtained through the interconnection of pre-existing or partially modified systems, system engineering is increasingly interested in the characterization of the properties of robustness and resilience by integrating other concerns, for example, threats that may affect the system at different stages of its life cycle [De Weck et al. 2011]. These new research fields make system engineering an evolving field, even if it has a corpus of almost half a century and many practical applications crowned with success. However, in the French academic world, the engineering of complex systems is still a relatively unrecognized discipline, whereas it is so in most Anglo-Saxon countries. That is all the more regrettable as it is a basic discipline for the complex systems industry, where France excels in certain fields such as transport, aeronautics, nuclear, and defense. The development of a chain from upstream to downstream can only be a major competitive tool to meet today's and tomorrow's challenges, for example, sustainable development.

2.2 Design process and product modeling

The approaches based on the product modeling propose representing the design product's functions and behavior (Figure 2.9). Among these, Function-Behavior-Structure (FBS) proposed by [Gero 1990, Gero & Kannengiesser 2004], characterizes the product's structure using its functions through its behavior. FBS framework exposed certain ambiguities, including the absence of a consistent function description

[Vermaas 2007]. Another theory that makes part of this second group is Axiomatic Design, proposed by [Suh 1990, 2001], which represents the product in four different domains: customer, functional, physical, and process. The design process goes back and forth between the four domains and uses two axioms to validate design choices: the independence axiom and the information axiom. [Albano 1994].

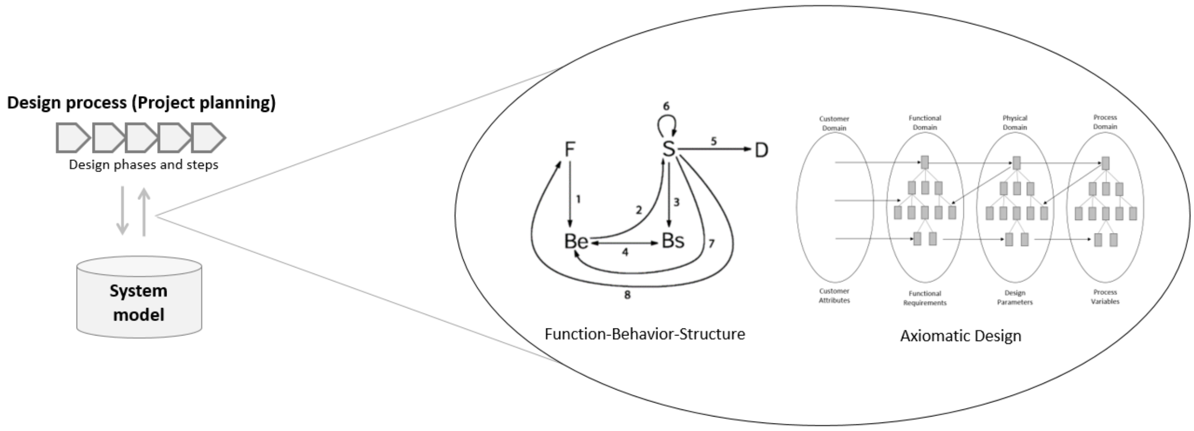

Figure 2.9 Design process Vs. Product modeling approaches.

2.2.1 Function-Behavior-Structure (FBS)

The model "FBS" was proposed by John S. Gero in the early nineties. It proposes to structure the design data of a product from three views [Gero & Kannengiesser 2004]. The first brings together those describing the functions of the product, which describes the aim of the object, i.e., what the object is for. The second one groups those relating to its behavior which describes the attributes derived or expected to result from the structure (S) variables of the object, i.e., what the object does. Finally, the third contains those defining its structure that describes the object’s components and their relationships, i.e., what the object is.

These variables are created and transformed by processes, which take place in three diverse worlds that are recursively linked together (Figure 2.10). The external world is made of representations outside the designer. The interpreted world is made of sensory experiences, concepts, and interpreted representations of that world with which the designer interacts. The expected world is the world in which the effects of the designer's actions are imagined according to the current goals and the interpretations of the present state of the world.

It is important to note that this product model is based on a limited number of design stages. Although it is comprehensive and consistent, its high level of genericity does not cover all design needs. For example, it does not allow to consider the intermediate design elements involved in the development of the organic architecture of the physical product. However, this step is crucial for monitoring the product throughout its life because it allows to control the impacts of changes.

The product model is simplified through a diagram allowing the design team to appreciate the interactions between each class of data from a dynamic point of view, as shown in Figure 2.11 and explained below.

1) Transformation of the functions characterizing the customer's needs (F) into an expected behavior of the product (Be).

2) Transformation of the expected behavior of the product into an architecture (S).
3) Evaluation of the real behavior of architecture (Bs).
4) Comparison of the measured behavior (Bs) with the expected behavior of the product (Be).
5) Detailed design of the product (D) from the selected architecture (S).
6) Changing of the product architecture (S) after the detailed design so that it remains consistent with the real product behavior (Bs).
7) Changing of the expected behavior of the product (Be) after the detailed design so that they remain consistent with the actual product behavior (Bs).
8) Change product features (F) during detailed design to remain consistent with actual product behavior (Bs).

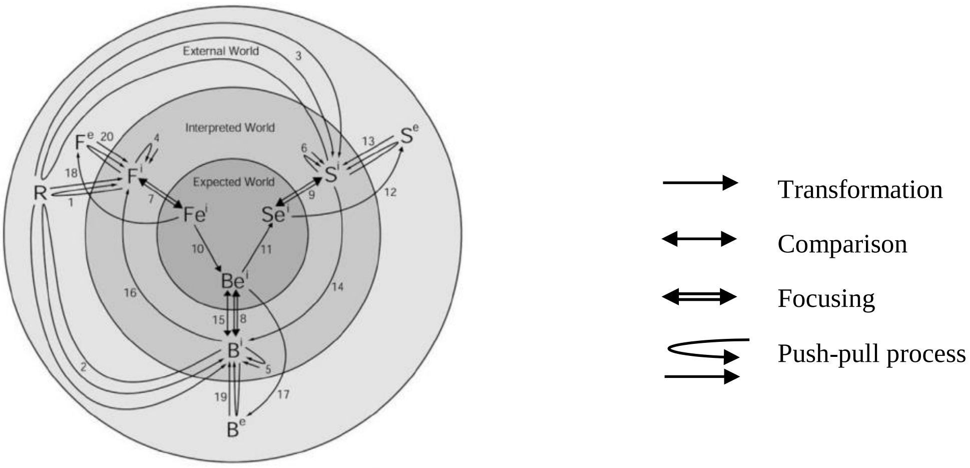

Figure 2.10 The situated FBS framework [Gero 2004].

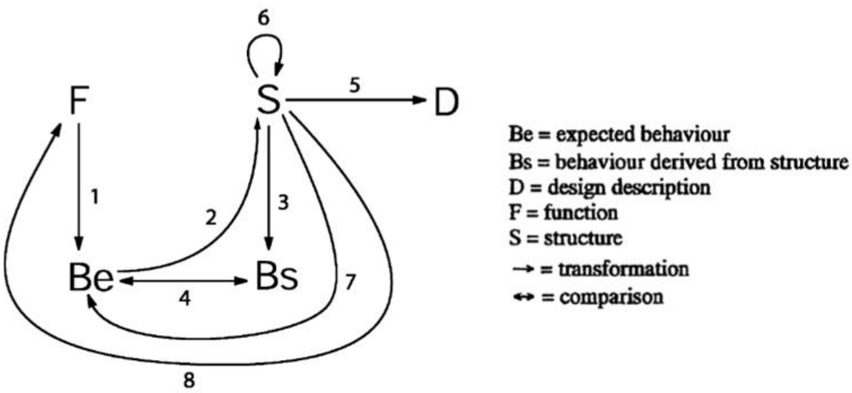

Figure 2.11 the product model "FBS" [Gero 2004].

Since its first appearance [Gero 1990], several articles have been written about the framework of Function-Behavior-Structure (FBS). Gero himself has further developed and integrated this model [Gero & Kannengiesser 2004]. The scientific debate on the FBS framework has revealed some ambiguities; These ambiguities include the lack of a stable definition of a function [Vermaas & Dorst 2007] and limitations, for example, in the representation of interactions between humans and machines [Wang 2002]. However, the FBS model remains a reference model for describing design processes and tasks.

2.2.2 *Axiomatic Design*

In another approach, N. Suh proposes to guide the designer in his work and his choices by drawing the design data from the definition of the customer's needs to the complete description of the product [Suh 1990, Suh 2001]. For this, they create an approach in the early nineties that they call "Axiomatic Design" based on the following premise: the design is a continuous interaction between what the designer must do and how it must be realized.

A precise framework consisting of four sequenced and complementary domains is fixed (see Figure 2.12). It contains:

1) A domain dedicated to the needs of the customer.
2) A domain grouping the functions that must fulfill the product.
3) A domain gathering all the physical parameters of the product.
4) A domain containing all the variables of manufacture of the product.

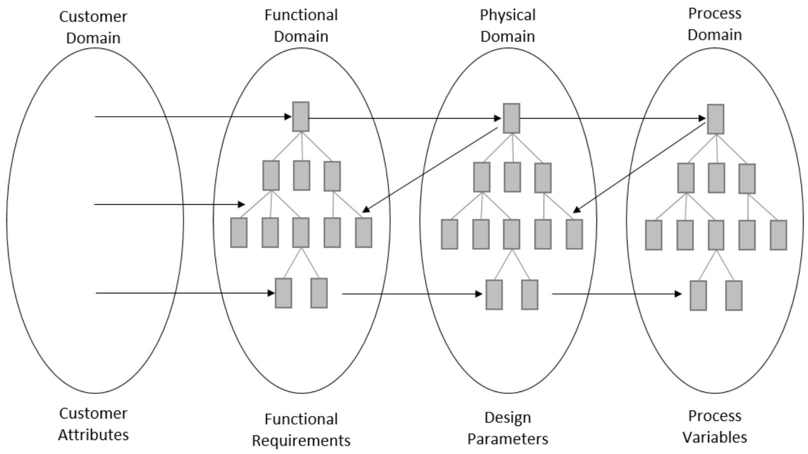

Figure 2.12 Axiomatic Design approach design framework [Djefel 2010].

It can be applied to all design activities, as the name "framework" implies. It is made up of two axioms. The Independence Axiom is the first one, and the Information Axiom is the second one. A good design should meet both axioms, whereas a bad design should not. The word "axiom" comes from geometry, as is well known. When a counterexample is validated, an axiom cannot be demonstrated and becomes obsolete. A counterexample has yet to be discovered in axiomatic design. Rather, a large number of practical design examples based on axioms are validated.

The following are design axioms derived from common engineering principles:

- First Axiom: Independence Axiom

    Maintain the FRs' independence.

    <u>Alternative Statement 1:</u> The independence of FRs is always maintained in an ideal design.

    <u>Alternative Statement 2:</u> DPs and FRs are coupled in an acceptable design in such a way that a specific DP can be modified to satisfy its associated FR without affecting other functional requirements.

The Independence Axiom states that the choices made in the preceding domain should satisfy the attributes in the following domain independently.

- The Information Axiom (Axiom 2)

  Reduce the amount of information in the design.

  Alternative Statement: The best design is one that is functionally uncoupled and has the least amount of information.

The Independence Axiom must be satisfied in axiomatic design. It is possible to develop multiple designs that satisfy the Independence Axiom. The best design should be chosen in this scenario. The best design is the one that contains the least amount of information.
The elements populating these four domains interact together in two different ways: through links of decomposition between the elements of the same domain and through links between two consecutive domains ensuring their coherence. Several rules allow to manage both types of links simultaneously. Two complementary axioms make it possible to analyze the relational structures created by the designer and help him in his decision-making. Although this approach is based on a global vision of the design activity by considering the interactions between the different domains, it focuses exclusively on the product without addressing other facets of the design activity, such as the organization.

Essentially, the axiomatic design can be used to create new designs or to evaluate current ones. It comes in handy while creating new product concepts. Although the approach has a limited history, its use has been demonstrated through several cases. Designers of applications have a few standard reactions. First, they readily accept the axioms and believe that they can use them right immediately. They are, however, having difficulty testing the axioms with their current products. Most of the time, they approach the designs with preconceived notions rather than from an axiomatic standpoint. At this point, many designers tend to abandon axiomatic design. If the designers can get over this level, they will see how valuable Axiomatic Design is.

2.3 Product and function modeling approaches

In this section, some product and function modeling approaches are explained to identify the main elements needed to integrate the product model into the design framework. According to [Brissaud & Tichkiewitch 2001], organizing ongoing information feedback loops from product users to designers and manufacturers can help enhance product design. Many authors have attempted to establish evolutionary design support approaches based on knowledge about the real characteristics of the product's working environment [Goncharenko et al. 1999]. These methods are mainly used for maintenance planning and analysis.

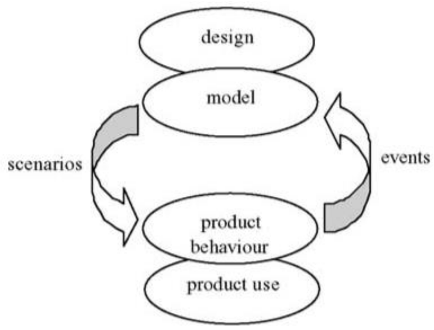

Figure 2.13 Interactions between product design and use [Brissaud & Tichkiewitch 2001].

They take into account the reciprocal engagement of design and maintenance operations, as well as the methods and possible benefits of product information circulation and use [Goncharenko & Kryssanov 1999]. Monitoring and fault diagnostic ideas have been defined [Van Houten et al. 1998]. Monitoring is the process of comparing a product's actual behavior to the behavior anticipated by a model (Figure 2.13).

2.3.1 Product modeling

A design team generates multiple virtual (digital) models of the product to describe its geometry, production and assembly procedures, mechanical planning, and performance, among other things. Such models must be able to link product behavior at every step of its life cycle, across a variety of circumstances (it is possible to consider here only standard product operation scenarios, but many others could exist). If there is a disparity between the predicted product behavior resulting from the scenario and the actual product behavior, this event must be recorded and assessed in the product model. Of course, the transmission of information to the models will impact the designers' design process in future works.

All of the research of new design systems that support concurrent engineering points out to a multi-view, multi-user product model for the design process [Roucoules & Tichkiewitch, 2015]. The goal of a multi-view product model like this is to allow any design actor (anyone who needs to intervene in the design process at any point during the product's life cycle) to arrange the product in a way that is appropriate for his or her activity and tools. The product structure must make sense in terms of the actor's specialized profession and expertise. Many perspectives have been defined, including functional, structural, manufacturing, assembly, and recycling perspectives. Created the entire integrated design system and methodology; the model representation is built on components, linkages, and connections showing how an integrated design system may facilitate designer cooperation.

Manufacturing point of view

The manufacturing perspective has been extensively researched. The technique for integer design and manufacture is provided in [Tichkiewitch & Veron 1998], focusing on particular trade tools to assist designers. Tolerancing is discussed in [Tichkiewitch & Brissaud 1999], which focuses on the interplay between product and process specifications. [Paris & Brissaud 2000] created the models that were utilized to design the machining process. The machining process planning model is made up of machining features and their machining relationships.

View of the assembly

The assembly viewpoint has received less attention. The assembly model is made up of assembly parts and the relationships that exist between them. Parts or features are assembly pieces, where a feature is a set of geometric elements and technical attributes that belong to a part and mat another part's feature. The terms "assembly relations" and "composition relations" are interchangeable. A typical consists-of relationship is a composition. The connection relation, which evaluates the functional relationship between two things and characterizes the linkage, is where most technical information is found (e.g., kinematics, contacts). [Tichkiewitch & Brissaud 1999] is an example of such a viewpoint.

View from the perspective of maintenance

[Van Houten et al. 1998] describes a model-based maintenance system in which product modeling is utilized as a reference for monitoring, fault identification, and breakdown avoidance. A functional model, a behavioral model, and a parameter model are among the models used for maintenance activities, according to him (a structural model very similar to the assembly model described above). These models can serve as "references" for maintenance tasks. In terms of maintenance, sensory data is analyzed to create a specific parameter model, which is then compared to the reference state model to arrive at a diagnosis. The product model entails comparing the values of component linkages on the one hand and the value of relationships due to the product's behavior on the other.

2.3.2 Function modeling

This subsection focuses on models that describe features of system operation and are used to aid in the conceptual design process. In the literature, there are several similar function models. Many are derived from systematic design techniques, while others are proposed spontaneously.

Different function models are specific regarding the addressed contents and how the represented functions are constructed, according to the discussion of the function models. Two examples of function models from use case-based modeling (a use case schematic with related activity diagram) are contrasted to a function tree in Figure 2.14 to demonstrate some of the variations in the contents and structure of represented information in different function models.

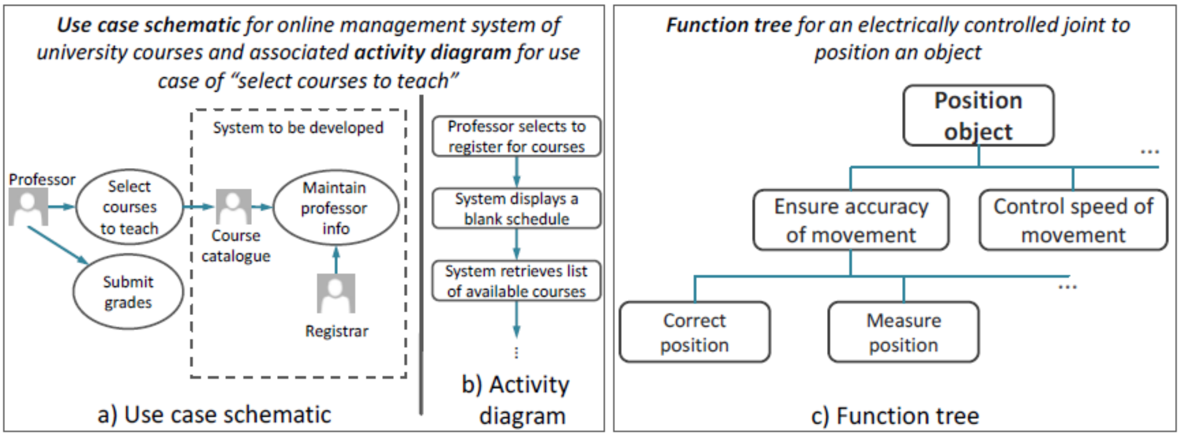

Figure 2.14 Examples of a) use case schematic and b) associated activity diagram, c) function tree [Eisenbart et al. 2014].

According to [Eisenbart et al. 2014], there are seven separate function modeling viewpoints: states, transformation processes, interaction processes, consequences, use cases, and technical system and stakeholder allocation. Several function models are used to handle various aspects of function modeling. Additional specific contents were discovered in a few models, which are mentioned at the conclusion of this section. The following sections detail the various viewpoints. The concepts are supplemented with examples of function modeling viewpoints based on a welding robot that connects metal sheets with welding tongs.

- States: Representation of the possible states of a system or the states of operands before to (input) and after (output) a transformation process. The most common operands are energy, material, and information specifications.
- Transformation processes: Representation of the processes carried out by function carriers (e.g., technical products, stakeholders) that are part of the system under development and may or may not result in a change in the state of the system or operands from the designers' perspective. Technical processes are transformations carried out by technical systems (e.g., technical products, sub-

systems); human processes are carried out by stakeholders involved in function fulfillment (this explicitly includes human activities, e.g., during service execution). Technical systems or stakeholders must give varied physiochemical impacts for transformation processes. The effects will be discussed later in this section.

- Interaction processes: Representation of interactions between stakeholders or other technological systems that are not part of the system under consideration and stakeholders or other technical systems that are part of the system under examination.
- Outcomes: Representation of the needed physiochemical effects must be supplied to permit, respectively support, transformation processes that alter the state(s) of operands and the system into a new state(s).
- Use cases: Representation of various scenarios for utilizing a technical system for a particular purpose (e.g., achieving a goal, changing the state of the system or user, and so on); this is typically associated with the interaction of stakeholders or another technical system with the technical system under development (interaction processes), which initiates, respectively requires, subsequent processes.
- Technical system allocation: The representation of the role of technical goods, subsystems, or other forms of (tangible or intangible) technical means functioning as function carriers in executing or enabling one or more functions; these technical means may be integrated into or interact with the system under examination.
- Stakeholder allocation: Representation of the roles of various stakeholders (humans or other animate entities), who may be users who profit from a system or function bearers who contribute to the system, for example, by carrying out needed activities or supplying resources.

In disciplinary and cross-disciplinary design literature, a wide range of function models are presented. Several diverse function modeling viewpoints and modeling morphologies were identified as a result of the accomplished review. Different combinations of these modeling views and modeling morphologies are addressed in the examined function models. None of the function models that were examined represented all of the defined function modeling viewpoints. Various function models may be incompatible due to the discovered differences, and designers working with different models may be unable to communicate their thoughts and design considerations. During conceptual design, this might significantly impede information interchange and common function modeling.

2.4 Design reasoning approaches

The interaction between the design phases and the design reasoning activities is unidirectional, describing that the design process directly affects those activities. That is why some other approaches rely on the designer's reasoning, where successive synthesis and analysis steps are performed to define the finished product's properties and characteristics (Figure 2.15). For example, Characteristics-Properties Modelling (CPM) proposed by [Weber et al. 2003; Weber 2005, 2009] is based on distinguishing a product's characteristics and properties. It offers a general framework as expressed by [Köhler et al. 2008] for other design theories, including [Hubka & Eder 1987]. In that group, it is also considered Design for Six-Sigma (DFSS) [Antony & Coronado 2002; De Feo & Bar-El 2002] a methodology conceived to improve the predevelopment of new products and services, providing a systematic way of managing products and resources and giving a pragmatic perspective of the design process [Treichler et al. 2002].

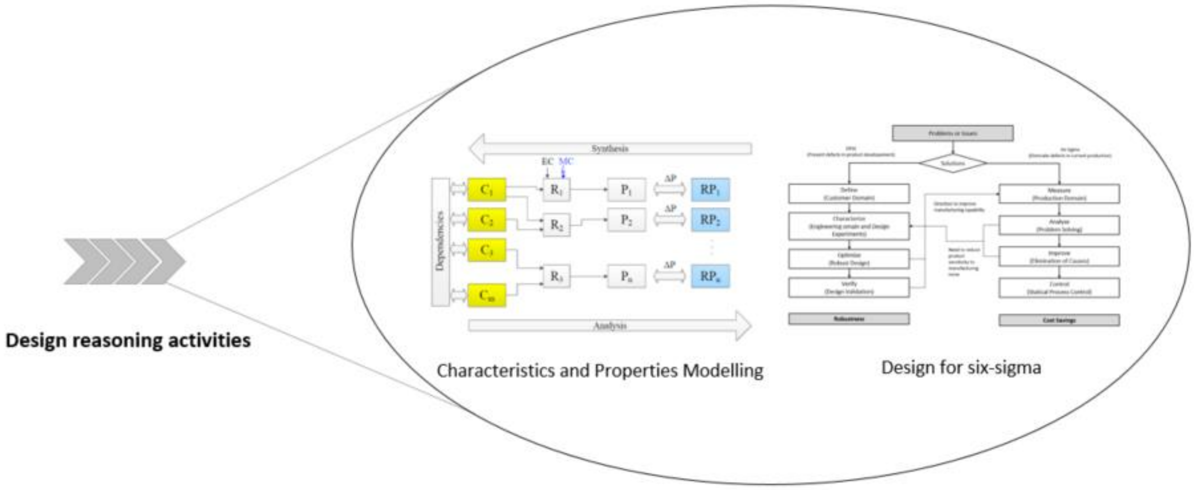

Figure 2.15 Design reasoning approaches.

2.4.1 Characteristics and properties modeling (CPM / PDD)

In addition to Property-Driven Development (PDD), CPM is proposed to explain the product development and design process [Weber et al. 2003; Weber 2009]. CPM / PDD is based on the distinction between "Characteristics" and "Properties" of a product [Tomiyama et al. 2009; Weber et al. 2003].

- Characteristics (Ci) are the parameters that can be directly influenced or determined by the designer. For example, the shape, structure, size, material, and surface of the product.
- Properties (Pj) are the behavior of the product. That means the designer's parameters cannot modify directly, but they can be modified indirectly through the features. For example, function, weight, aesthetic properties, safety and reliability, cost, manufacturability.
- Properties required (RPj) are the parameters that the designer/client wishes to achieve.
- Relations (Rj) represent the interrelationship between features and properties.
- External conditions (ECk) are defined by the external environment in which the designer has no control.
- Conditions of modeling (MCn) are the set of assumptions, boundary conditions or simplifications, used while developing the model, which must be taken into account to define the relations between characteristics and properties " [Dantan et al. 2013].

Relationships correspond with two main activities:

- Analysis; According to the known characteristics/data of a product, its properties are determined or, if the product does not exist yet in reality, predicted.
- Synthesis; Depending on the properties given/required, the product's characteristics are to be determined. The development/design process begins with a list of required properties. The designer's task is to find models of appropriate solutions and determine/affect their respective characteristics in such a way that the required properties are fulfilled to the customer's satisfaction [Weber et al. 2003].

PDD, the modeling process method, describes product development using the steps of analysis, synthesis, and evaluation. In general, the process begins with the requirements list (RPj). The first step of synthesis is to define the characteristics (Ci) according to the needs. The next step is to analyze the characteristics that result in properties (Pj). Then, it is the evaluation step in which ΔP is created by comparing RPj with Pj. That was the first cycle, then iteration after iteration, the product becomes more and more detailed (Figure 2.16). This process ends when all characteristics are assigned, and all properties can be determined/predicted, and also when $\Delta P \rightarrow 0$ with sufficient security and accuracy.

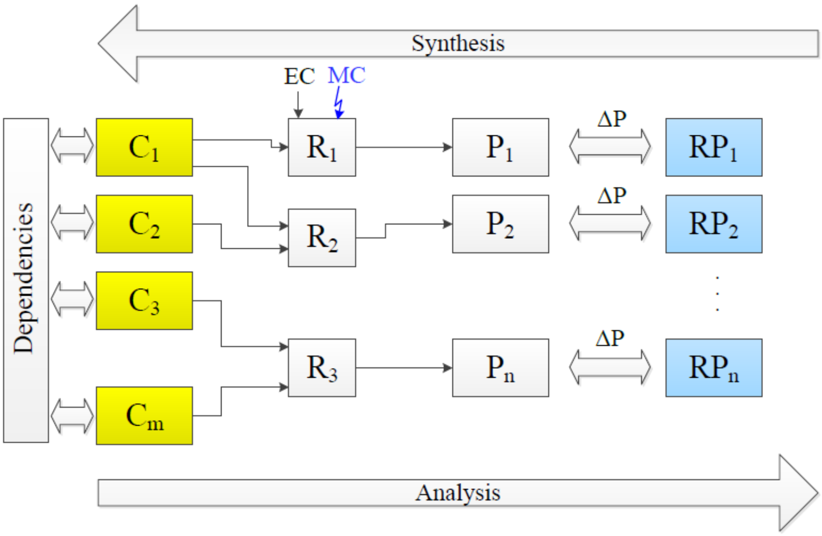

Figure 2.16 CPM/PDD representation extracted from [Köhler, et al., 2008]

CPM creates a unique language for designing a robust product. Thus, it is an appropriate method for integrated design. CPM / PDD has a general and systematic approach and is adapted to the design phase of implementation. It provides a framework in which other DTMs such as AD, [Pahl et al. 2007, Pahl & Beitz 1996], and [Hubka & Eder 1987] can adapt. It also provides support for integrating other methods such as DfX. In addition, it can explain some open-design theories, and it provides a theoretical basis for the development and use of methods and tools in the development process, including CAX [Deubel et al. 2007, Tomiyama et al. 2009]. Moreover, he works with mathematical relations, and, finally, he is adapted to model systems with the complexity of the design. However, the Weber model has some disadvantages when it has to deal with complexity in IPPD. In addition, CPM is introduced for product design only.

2.4.2 Design for six-sigma

Six Sigma is a fact-based, data-driven quality improvement philosophy for which defects prevention prevails over detection. This approach leads to customer satisfaction and operational results by reducing variation and waste, resulting in acquiring a competitive advantage. Six Sigma finds an application wherever variation and wastage exist, and all employees must be involved. A six sigma quality performance represents only 3.4 defects per million parts.

Design for six sigma (DFSS) is developed from Six Sigma, and it is a methodology to enhance new product and service development processes, and it provides a more systematic way to manage the deliverable, resources, and trade-offs. It helps to deliver better products and services that customers want and are willing to pay for.

DFSS is a relatively recent technique in comparison to six sigma and is explored by several researchers. However, the majority of previous work believes that DFSS is a proactive strategy that emphasizes designing well the first time. DFSS may be defined as a "rigorous and disciplined approach to design that guarantees new designs fulfill customer needs at launch" [El-Haik & Roy 2005]. According to GE corporate research and development, the value of DFSS lies in anticipating design quality in advance and driving quality measurement and predictability improvement throughout the early design phases [Treichler et al. 2002]. DFSS may alternatively be defined as a data-driven technique built on analytic tools that enables users to avoid and forecast errors in a product or service's design [De Feo & Ber-El 2002]. The DFSS strategy is centered on finding novel methods to meet and exceed client needs. This may be accomplished by maximizing the design function of the product or service and then confirming that the product or service fulfills the client requirements [Antony & Coronado 2002].

Additionally, the research focuses on the distinctions between six sigma and the DFSS method. While DFSS is proactive, unlike six sigma, it lacks a unified approach [Hoerl 2004]. DFSS employs a variety of techniques, including the following:

- IDOV (Identify, Design, Optimize, Validate)
- IDDOV (Identify, Define, Design, Optimize, Validate)
- ICOV (Identify, Characterize, Optimize, Validate)
- DCOV (Define, Characterize, Optimize, Verify)
- DMADO (Define, Measure, Analyze, Design, Optimize)
- DMADV (Define, Measure, Analyze, Design, Verify)
- DMADOV (Define, Measure, Analyze, Design, Optimize, Verify)
- DCCDI (Define, Customer Concept, Design, Implement)
- DMEDI (Define, Measure, Explore, Develop, Implement)

Other distinctions include the following:

- DFSS is a technique that incorporates concerns raised by end users at the design stage, whereas DMAIC addresses operational difficulties.
- In comparison to six sigma, where benefits are expressed primarily in financial terms and obtained relatively quickly, DFSS benefits are difficult to quantify and are obtained over time.
- In comparison to DFSS, where radical improvements are possible, the DMAIC methodology tends to provide incremental improvements.

While six sigma and DFSS techniques differ, they complement one another, as seen in Figure 2.17. The first step is problem definition, during which client needs are integrated. This is followed by the stage of characterisation. At this step, a model of the problem in the process or engineering domain is constructed. The term "model" refers to the process of converting the customer's voice and use conditions into a technical system [Ferryanto 2005]. As seen in Figure 2.17, at the characterization step, improvements from the DMAIC are included into the model. Following model development, the most optimum and resilient solutions are discovered. Finally, the solutions are evaluated for their utility in resolving the original problem.

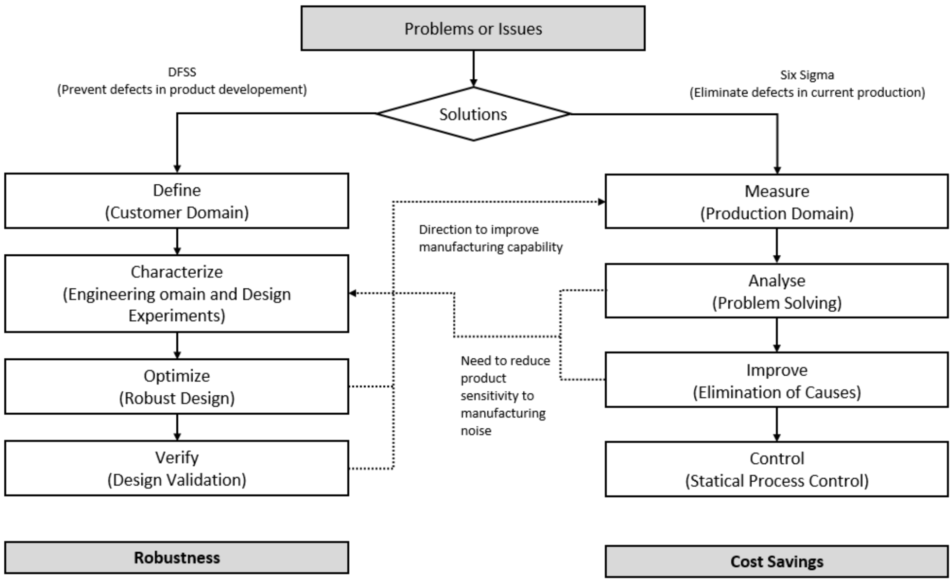

Figure 2.17 DFSS versus Six Sigma [Ferryanto 2005]

Here below are presented in a more detailed way four of the most used methodologies of DFSS. These tables will allow the reader to understand the different steps inside each phase to analyze overlaping, redundance, and lack of activities throughout the whole process. For this study, it is important to define a fixed framework in terms of the designer's activities to clarify as much as possible each step of the process.

The approach of DFSS is suitable for this goal because it allows to describe the steps to follow from the designer's point of view to develop the intermediate objects of the process. To do so, a generic methodology will be proposed based on the different elements described in this section.

3. Safety integration in design

Regarding human factors integration into the design process, the literature review has pointed out three main approaches: first, safety assessment tools to evaluate working situations [Chinniah et al. 2017; Fadier & Ciccotelli 1998; Houssin et al. 2006; Houssin & Coulibaly 2011]. As seen in Figure 2.18, those safety assessment tools are directly applied to the design process either on one or several steps. Some researchers consider that traditional safety analysis tools during the design process are enough to identify dangerous situations [Harms-Ringdahl 1987; Gauthier & Charron 2002]. Others use virtual tools to address the same safety risks [Dukic et al. 2007]. For [Ericson 2015], the safety analysis can be qualitative, semi-quantitative, or quantitative. For [De Galvez 2017], risk identification can be narrowed down to the energy flow inside a system.

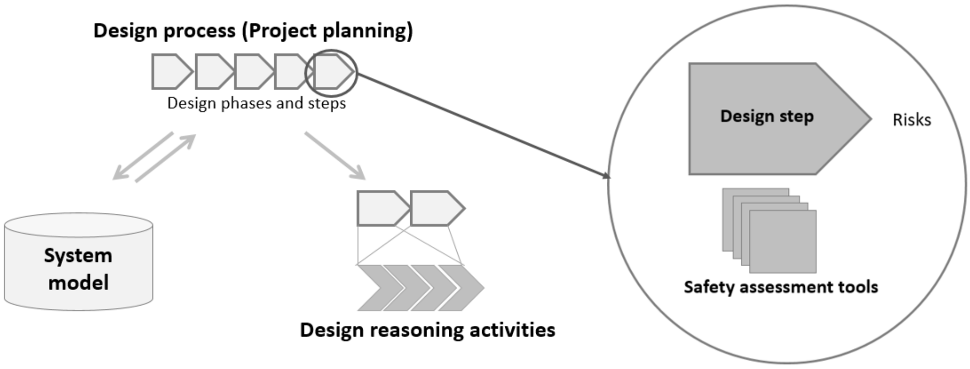

Figure 2.18 Design processes.

Second, design for safety includes safety requirements as an intrinsic property of the system [Wang 1997; Rasmussen 1994]. As seen in Figure 2.19, dedicated system models and design steps are proposed to meet safety requirements. Some research works have applied design theories and methods to improve safety in production systems in the literature. For example, that is the case for [Van Duijne et al. 2007] and [Fadier & De la Garza 2006].

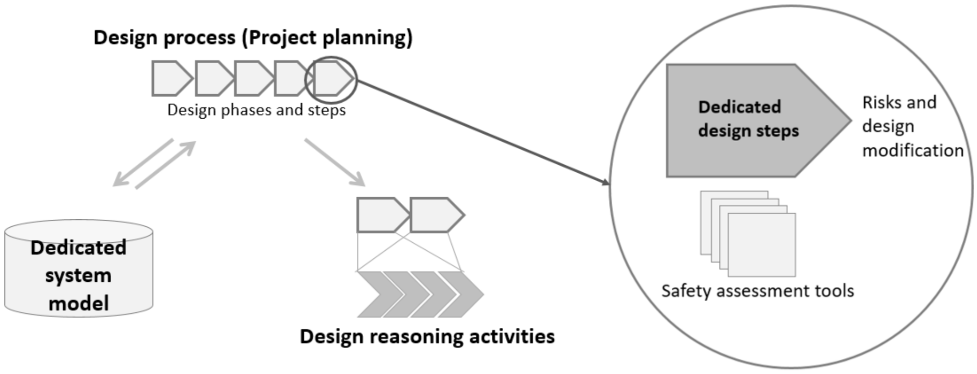

Figure 2.19 Design for safety.

Third, the design methodologies and safety assessment tools that are developed or adapted to work simultaneously are part of the same design process but are not only focused on safety parameters, and risk detection such as IRAD and design for safety applied to FBS [Slatter et al. 1989; Sadeghi et al. 2017] or Axiomatic Design in ergonomics [Helander & Lin 2002]. Some of these works propose using energy flow to evaluate the level of risk of a production system, so the system modeling needs to be based on energy flow. As shown in Figure 2.20, these approaches propose variants of some of the widely used design theories and methods found in the literature, such as Function-Behavior-Structure [Gero & Kannengiesser 2004] and systematic engineering [Palh et al. 2007].

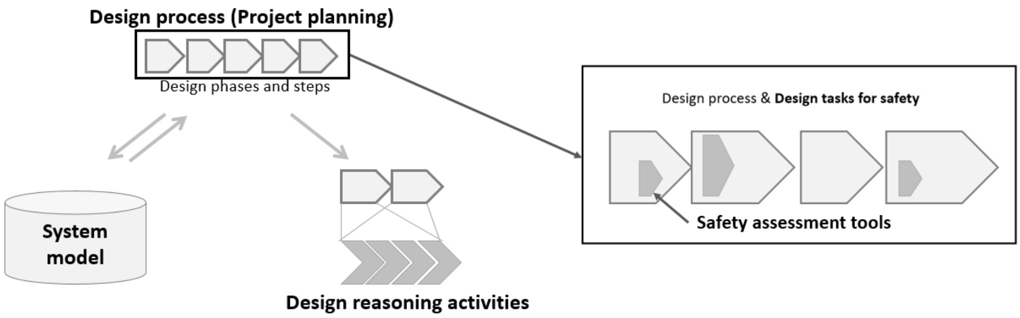

Figure 2.20 Design process and tasks for safety.

The variety of topics and the number of research related to improving safety during the design process make it difficult for researchers to overview the field thoroughly. [Sadeghi et al. 2016] classified those approaches into two main research groups and provided the elements to consider in the case of design for safety (Figure 2.21). Following discussions on research topics from a chronological and thematic perspective, two main research findings were obtained. On the one hand, most of the solutions proposed for design for human safety intervene quite late in the design process. On the other hand, the remaining solutions do not explicitly consider application conditions during the early design phases.

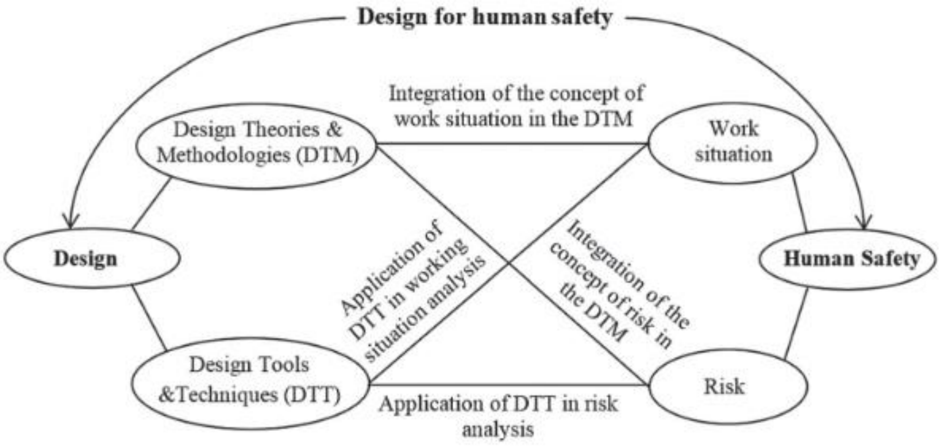

Figure 2.21 Framework of Design for Safety [Sadeghi 2016].

3.1 Working situation concept

From the ergonomics point of view described in [Pomian et al. 1997], the global working situation was established by merging historical data related to public health, personnel and production management, and the company itself (e.g., raw material supplies, the marketplace of the company). The definition related to safety during the design process is a more local working situation, one that is defined at the machine level. It has nothing to do with its market position, partnerships with raw material suppliers, or finished product delivery (Figure 2.22).

This idea is referred to as a "Working system" by [Hasan et al. 2003]. The working system comprises one or more persons and their tools of the trade who work together to complete one or more tasks inside the working area in the working environment under the conditions of the task at hand. When one person is exposed to one or more harmful phenomena, the situation becomes risky.

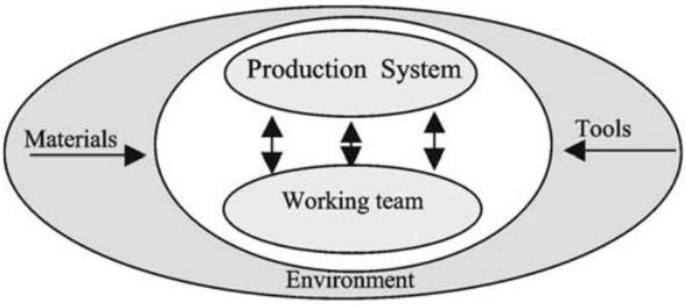

Figure 2.22 Macro view of the Working situation [Hasan et al. 2003].

The properties that characterize the concepts offered by the entities in the system model are defined by [Harani 1997, Bernard & Hasan 2002, Hasan et al. 2003]:

- Type of situation
- Organization
- Raw materials
- Finished product
- Type of stock
- System
- Parameters
- Mode of intervention
- Working team
- Tools
- Dangerous event
- Consumable
- Hazard or dangerous phenomenon
- Utilization Task
- Dangerous zone
- Environment

3.2 Safety assessment methods and tools

New processes mean new and emerging risks (NER) [Brocal & Sebastian 2015]. So, it is important to give tools to designers in order to prevent these risks from the beginning (design process). Multiple methods have been proposed in the literature: [Coulibaly et al. 2008; Shahrokhi & Bernard 2009; Ghemraoui et al. 2009; Hasan et al. 2003; De Galvez 2017], most of them aiming to identify, quantify and qualify hazardous situations through an analytical way.
According to [MIL-STD-882D 2000], safety is “freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.” Based on this definition, safety could be viewed as the absence of unwanted events. [Aven & Renn 2009] has listed eleven definitions of risk, which are found between 1976 and 2008. Then, he proposed to divide risk definition into three categories:

- Risk is expressed by means of probabilities and expected values.
- Risk is defined as an event or a consequence.
- Risk is expressed through events/consequences and uncertainties.

3.2.1 Risk assessment

The ISO standard 12100 ‘Safety of machinery - General principles for design – Risk assessment and risk reduction’ [ISO 12100 2010], proposes a risk detection method, which is applicable on implanted work cells, workstations, machines, or modules:

- Determination of the limits of the machinery
  - Use limits
  - Space limits
  - Time limits
  - Other limits

- Hazard identification
  - Human interaction during the whole life cycle of the machine
  - Possible states of the machine
  - Unintended behavior of the operator or reasonably foreseeable misuse of the machine

- Risk estimation
  - Elements of risk
  - Aspects to be considered during risk estimation

- Risk evaluation
  - Adequate risk reduction
  - Comparison of risks

This method is useful to detect and reduce hazardous situations, but not during the design process. It is important to say that traditional methods focused only on correcting the problem once it occurs or at the late stages of design, increasing the amount of resources needed to fix or prevent the damage.

3.2.2 Safety Indicator (SI)

[Coulibaly et al. 2008] propose a safety assessment based on a Safety indicator as the product of a Factor of Risk (FR) and an Index of Risk (IR). FR indicates the existence of a risk or not and combines three Boolean parameters: Ph (existence of a hazard), Zo (existence of a hazardous area), and HIn (intervention of a worker in the hazardous area). On the other hand, IR is related to quantification and qualification of risk and combines four of these parameters: Gr (gravity of risk), Ex (exposure duration and frequency), Pr (probability of a dangerous event happening), Av (probability of avoiding a dangerous phenomenon). Nevertheless, the paper does not talk about the identification of these parameters.

3.2.3 Performance Analysis Agent (PAG)

[Shahrokhi & Bernard 2009] suggest a multi agent-system called PAG (Performance Analysis Agent), which analyses work situations through numerical mannequins. These models consider a global human-centered set of agents: morphological, biomechanical, kinematic, physiological, and psychological. In addition to that, the analysis considers human factors, risks, economic and industrial performance. This approach is easily adaptable for the designer, but it intervenes too late in the design process since it is based on a numerical model.

3.2.4 Innovative Risk Assessment Design (IRAD)

The method proposed by [Ghemraoui et al. 2009] applies both technical and safety functions during the design process while communicating with a risk process. This last one is divided into three stages called risk interactions, which are: human–principles interaction (HPI), human-system interaction (HSI), and human-machine interaction (HMI). The designer can apply the method through the design process to satisfy all safety requirements. However, the method does not propose a hazard identification solution.

3.2.5 Work Situation Model (MOSTRA)

[Hasan et al. 2003] suggest the MOSTRA model (in French: MOdèle de Situation de TRAvail), which enables concurrent evaluation of many perspectives on data based on the idea of risk. While this model describes every connection between the ideas that comprise a work scenario, it does not make a direct connection between design parameters and risk evaluation parameters. As with the prior method, MOSTRA does not provide danger identification solutions.

3.2.6 Energy Analysis for Systematic Hazard Identification (EZID)

[De Galvez et al. 2017] propose a method based on the relation between energy flow and risk in a production system. EZID (‘Energy analysis for systematic haZard Identification during Design) was conceived to be applied from the beginning of the design process to identify all types of hazards (mechanical, electrical, thermal, vibration, noise, radiation, material/substance, and ergonomic).

Figures 2.23 and 2.24 show a classification of the different resources found in the literature based on abstraction level and maturity of the product how they can be applied in the design process. This classification allows the reader to understand better where and when a health and safety analysis can be performed and how it is placed following the different levels of abstraction.

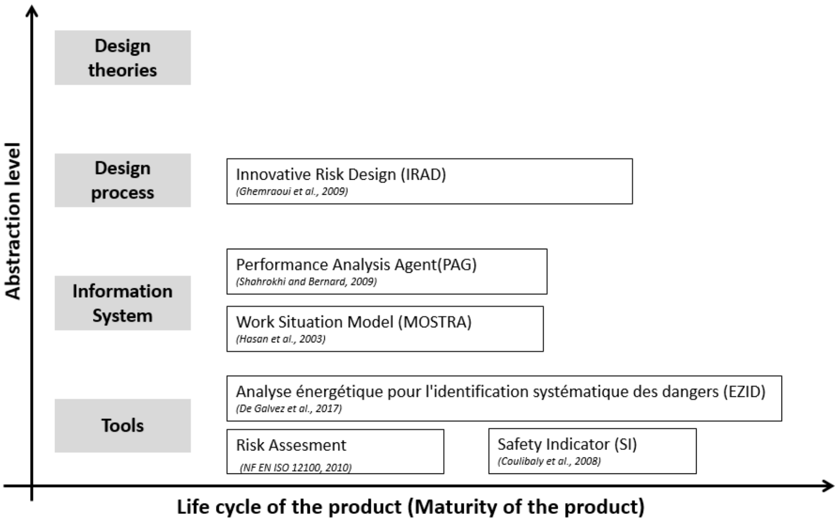

Figure 2.23 Classification of the different health and safety resources.

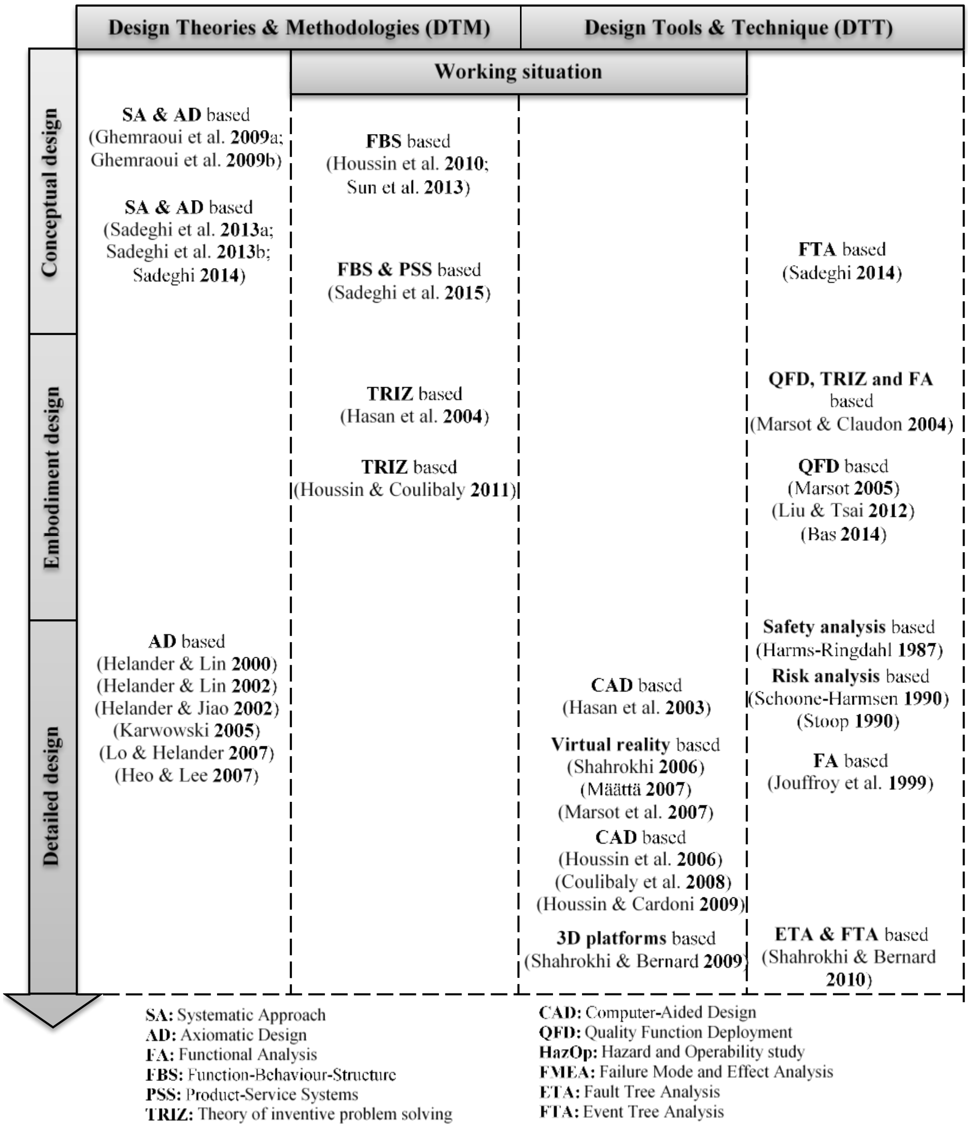

Figure 2.24 Researches in design for human safety [Sadeghi et al. 2016].

4. Literature review conclusion

This literature review has brought multiple aspects to the table regarding design, health, and safety. As it has been exposed, the different design methods and theories found in the literature focus on specific viewpoints that sometimes disregard crucial elements for the success of the final solution. Most of the design processes proposed by other authors lack completeness when considering that the activity of designing is only based on the project or in the product itself. This chapter aims to show the research done in this field, its results, and how they can be applied in a different methodology that regroups their principal constituent elements and allows the designers to follow a structured step-by-step design procedure.

The systematic design focuses too much on the project, which leaves other aspects of the design process unattended. Nevertheless, Pahl & Beitz have settled the main framework for a structured process through all designing stages and is the basis for the methodology proposed from the project's point of view. DFSS has an interesting approach to the activities of the designers and proposes chronological steps that guide the user to get the expected result. In this study, a generic methodology of DFSS has been used to support the point of view of designers' activities. Systems engineering is one of the most complete methods among those researched, but its weakness resides in the designer's activities point of view. For this project, it has been decided to use the product approach proposed by systems engineering because it gives special attention to the product being at the same time compatible with the other aspects considered for the project.

As the reader can see, all the approaches have strong and weak aspects and a wide range of points of view focusing on different parts of the design. So from this scope, the idea of applying them simultaneously to have a complete much more complete method arises, but it is not possible because they are not compatible enough to be used in the same project. One of the objectives of this thesis is to propose a method that includes the most useful aspects of the methods described earlier to have a robust and useful methodology to use in the industry.

In terms of design methodology, a decision had to be made among the different options present in the literature. One of the two possible options was to combine the most performant methodologies of each approach (project, product, and design reasoning) to have a comprehensive design methodology. However, the problem of this solution is the incompatibility of most of the methodologies found in the literature. The second option was to enrich the most homogeneous methodology or methodologies to have a solid base. This last option was chosen for the next steps, so based on the analysis made in this chapter, the most homogeneous methodologies following the axis of analysis are System Engineering and Systematic design.

The human factor integration approaches only give guidelines for production systems design, and only a few studies have proposed collaborative safety-design frameworks. This conclusion suggests that it is necessary to analyze the required parameters for a safety assessment and regroup them in a general design framework. Energy characterization needs to be used to model the system's behavior to integrate human safety factors and assessment. The project planning approaches present a proper design framework as the main guideline for an integrated design method. The well-defined phases proposed in these theories provide solid ground to integrate elements of other approaches. Design reasoning theories give the designer analytical tools applicable all along with the different phases of a general design framework. These tools represent actions or activities that lead to practical solutions to design problems, which can be applied iteratively in different contexts. Product modeling design gives objectives to be accomplished in terms of time, cost, and performance, directly related to the product incorporated into a general framework. These findings have been integrated into the proposed method introduced and explained in the following chapters.

Chapter 3: Design process and design reasoning

Abstract

This chapter presents the elements considered for the definition of the design process and design reasoning activities. From the different design approaches explored in the literature review, multiple elements have been adapted to be part of a more robust design framework compatible with human factors and safety assessment. Those elements are explored in more detail in this chapter to understand better the thought process involved in the definition of the proposed approach. Regarding the design process, a comparison with the Systematic design approach is used to explain the main differences and changes made. The phases of task clarification and conceptual design are detailed for both approaches. Regarding the design reasoning activities, the five main activities specify, design, model, evaluate and optimize, and validate are proposed based on the definitions used in design for six-sigma. The different concepts needed to follow through the phases are exposed and discussed considering the iterative nature of these activities. Finally, the chapter concludes by defining the link between the design process and the design reasoning activities explained using a matrix-like representation of the proposed design method.

1. Introduction

This chapter describes the proposed design framework's needs and requirements and defines its principal aspects. Based on the literature findings, a general design method must meet design objectives in terms of cost, time, and performance (development and production), respect constraints related to industrial practices and the industrial environment, and integrate decision-making tools expertise such as human safety. The design method to meet those requirements needs a general framework, decision-making tools adaptable to multiple and variable criteria, and the required information to model and analyze the final result (production system). In the following sections, the integration of those three aspects is explained.

The general framework structures the design process, so it must provide well-defined design objectives (in terms of cost, time, performance of the final solution as well as intermediate objectives to achieve during the design process), sequential design phases, and well-defined results at the end of each phase. The proposed method uses a modified version of the general design framework proposed in project planning design theories [Pahl & Beitz 1996, Pahl et al. 2007], composed of four different phases: Task Clarification, Conceptual Design, Detail Design, and Manufacturing Assessment. These four phases provide a guideline for the development of the design project following a logic sequence. At the end of each phase, there are expected results used as input for the following phases. Figure 3.1 shows the three elements that form the integrated framework: phases, steps, and reasoning activities. This representation is proposed to identify basic design tasks that integrate the three points of view.

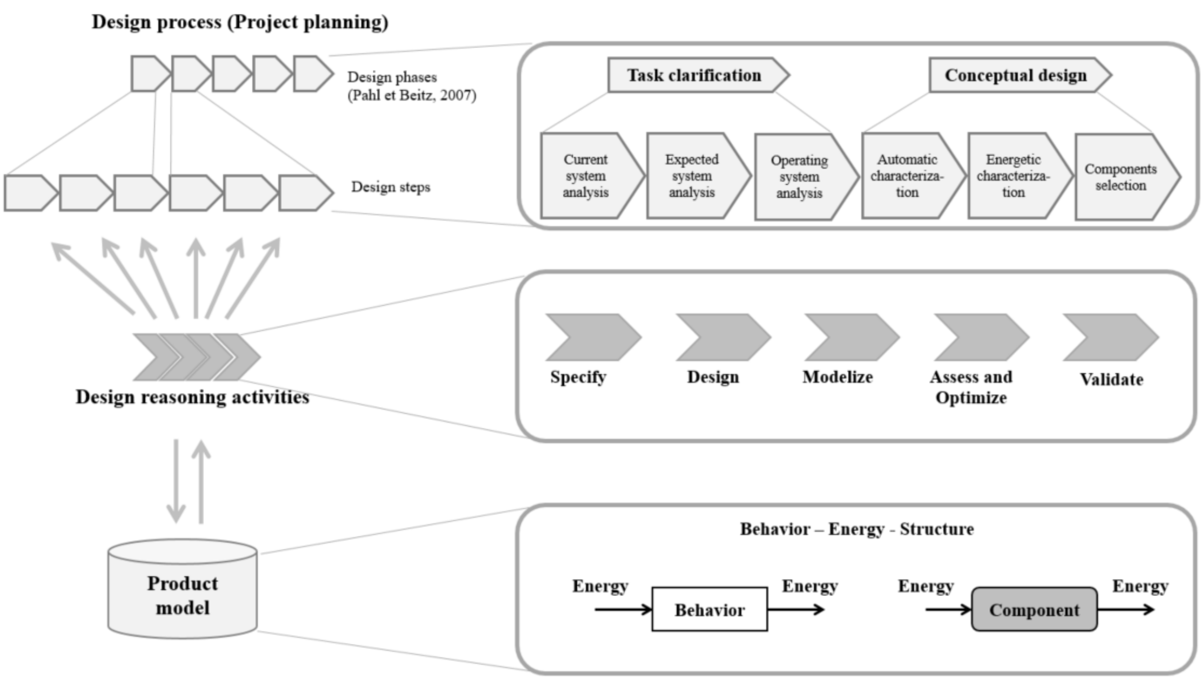

Figure 3.1. Proposed design framework.

2. Design process

The proposed method is based on a modified version of the phases proposed by [Pahl et al. 2007]. The focus of the thesis is the first two phases of the design process: task clarification and conceptual design. The decision to concentrate on those two phases is based on the importance of defining a solid ground for any design project and the fact that the objectives, requirements, and constraints need to be fully defined in the early phases of the design process. The decisions taken during the first two phases of a project have a significant impact on the following phases. Combined with the fact that the time and, therefore, the cost of development evolves exponentially over the phases, it is possible to conclude that the success of a design project depends mainly on these decisions. The last phases have been widely studied, and the current methods provide sufficient tools to be applied after the conceptual design phase.

To understand the proposed approach, it is necessary to define two complementary concepts, the operating and operated systems (Figure 3.2). The operating system is defined as the aggregation of multiple components that interact and perform Basic Functions to achieve a specific goal or mission. The operated system is defined as the aggregation of multiple stakeholders that interact with the operating system elements affecting and being affected by it. The objective of the proposed approach is first to identify the operated system to define the boundaries of the design problem and see the area of action of the final solution, and secondly, fully define the properties and characteristics of the operating system (final result of the design process) and how it affects and is affected by the operated system.

This method's contribution relies firstly on the interactions between the different elements that conform to the design process and secondly on exploiting that structure to obtain the required information for a successful design project. That information is obtained and treated from the early steps of the process by evaluating the environment and the current state of the production system and then by characterizing its expected behavior. The three elements introduced in the literature review (design phases, system model, and design reasoning activities) have not been fully integrated into any of the existing design methods and theories, which is one reason why the proposed approach uses an energy-based system model. The introduction of energy has two main objectives: first, to facilitate the transition from functional to organic architecture (discussed in Chapter 4), and second to facilitate analyses such as those on the safety of operators (discussed in Chapter 5).

To explain the changes and modification, the original systematic design proposition of the first two phases is explained in the following sections, and then, the new proposition is presented based on the modifications and the proposed criteria. One aspect worth mentioning is that the study object of the proposed method is specifically a production system. On the other hand, the systematic approach considers the product as the study object. That difference makes that in the systematic approach, the focus is the usage of the product, while on the proposed approach, the focus is on the properties of the production system itself, the product it will produce, and the manufacturing processes involved.

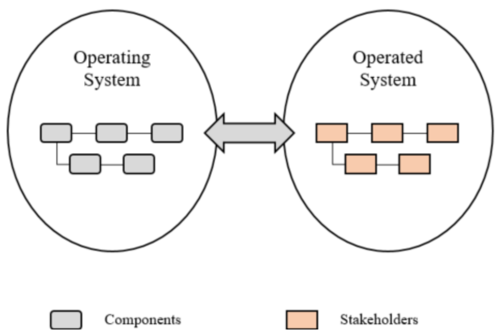

Figure 3.2 Operating and Operated systems interactions.

2.1 Task Clarification

Task clarification collects information on the criteria that the product or system must satisfy current restrictions and their relevance. This activity results in the specification of information in the form of a requirements list focused on and tailored to the design process's and subsequent working steps' interests. This document, which must be updated continuously, should serve as the foundation for the conceptual design phase and subsequent phases. Generally, the design task is presented to the design and development department as a development order (from outside or from the product planning department in the form of a product or system proposal), as a definite order, or as a request based on, for example, suggestions and criticism from sales, research, test, or assembly staff, or from within the design department. In the following subsection, the systematic approach of task clarification proposed by [Pahl et al. 2007] is explained in more detail, as well as the main differences with the proposed approach of this research work.

2.1.1 Systematic approach

In the Systematic approach, the task clarification phase includes statements about the product's functionality and performance, as well as information about deadlines and cost targets. The design and development department is faced with the challenge of identifying the requirements that govern the solution and embodiment and formulating and documenting these requirements quantitatively to the extent possible. To accomplish this, the following questions must be addressed collaboratively with the client or proposer:

- What are the expected outcomes of the proposed solution?
- What characteristics must it possess?
- What properties must not be included?

This process produces a requirements list which serves as the specification against which the design project's success can be measured. In this approach, the design and development department should conduct the task clarification process described in Figure 3.3 to define the product's current state, identify potential future developments and establish a requirements list. There are two stages to the procedure. The first stage is to define and record the most evident requirements. The second stage refines and extends these requirements through the use of specialized methods.

When creating a detailed requirements list using the systematic approach, it is critical to define the objectives and the conditions under which they must be achieved. As a result, the resulting requirements must be classified as demands or wishes. Demands are non-negotiable requirements; in other words, if any of these requirements is not met, the solution is unacceptable.

Wishes are defined as requirements that should be considered whenever possible, perhaps with the caveat that they justify only minor cost increases, such as central locking or reduced maintenance. It is prudent to categorize wishes as major, moderate, or minor.

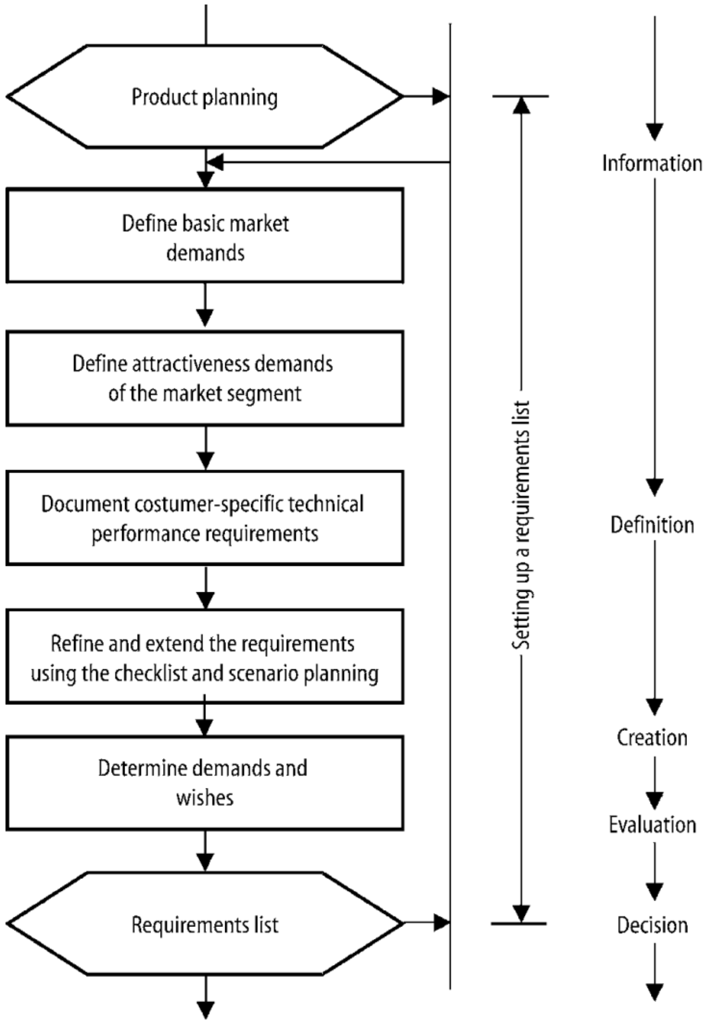

Figure 3.3. Steps for creating a requirements list proposed in the systematic approach [Pahl & Beitz 2007].

The distinction between requirements and wishes is also critical during the evaluation stage, as the selection is contingent on the fulfillment of requirements, whereas evaluation is limited to variants that already meet the requirements. Even before a specific solution is chosen, a list of requirements and desires should be compiled, along with quantitative and qualitative data. Only then will the resulting data be sufficient:

- Quantity: All data that contains numbers and magnitudes, such as the quantity of items required, the maximum weight, the power output, the throughput, and the volume flow rate.
- Quality: All data involving permissible variations or special requirements, such as waterproofing, corrosion resistance, shock resistance, and so on.

The systematic approach says that requirements should be quantified whenever possible, and they should be defined in the most straightforward manner possible. Additionally, special indications of significant influences, intentions, or procedures may be included in the requirements list, which serves as an internal digest of all the requirements and wishes expressed in the language of the various departments involved in the design process. As a result, the requirements list reflects the initial stage of the development process and serves as an up-to-date working document, as it is constantly reviewed.

The primary challenge in developing a requirements list is the quantity and quality of documents and data supplied with the design task. Depending on the engineering discipline, not all expected product properties are defined and documented. The remainder is implicit requirements that are expected by customers but not stated explicitly. As a result, the following questions must be addressed:

- What is the true nature of the issue?
- What implicit desires and expectations are at work here?
- Do the constraints specified actually exist?
- What development paths are available?

It is critical for the design and development department to have a firm grasp of the customers or market segment in question. Frequently, the requirements list is based on a contract signed with a customer, which typically includes the agreed-upon product properties and performance data, as well as product liability regulations and applicable guidelines.

The first exploratory step is to translate the contract's statements and requirements into product-relevant parameters that designers and engineers can apply. That is relatively simple to accomplish because a contract's product specification contains explicit requirements. A more significant issue is how to deal with implicit requirements; while they are not expressed, they still have a significant negative impact if they are not met.

Fundamental requirements are always implicit and not articulated by the customer. Their fulfillment is self-evident and critical to the customer's satisfaction. These requirements dictate whether a product succeeds or fails. For instance, a customer generally expects a follow-on product to reduce energy consumption and operating costs. The design and development department must understand the significance of these implicit requirements. The sales department or product management must provide information on these requirements, as well as the customers' thoughts and expectations.

Technical performance specifications are explicit specifications. They are articulated by the customer and are typically precise in their specification. Customers use concrete values to compare competing products and determine the significance of individual parameters.

Again, attractiveness requirements are implicit. Although customers are typically unaware of these, they are used to differentiate competing products. Customers are generally unwilling to pay a premium for these additional product properties. Consider the case of a motor vehicle, where such requirements include the number of standard colors and the possible combinations of external and internal color schemes.

2.1.2 Proposed approach

The definition of the task clarification phases of the systematic approach exposes the main elements to be considered to define a requirement list. However, it does not provide a structured set of steps to follow to fully define an exhaustive requirements list that contains the information needed during the different phases and steps of the design process. There is the exhaustiveness aspect, but also the perception aspect. It is important to note that a client perceives his needs through the filter of his culture and experiences. Moreover, it is the same with the designer. It is therefore essential that both agree on a common perception of the need. The generalization of the task clarification phase is understandable, considering that every design project has different objectives, requirements, and contexts. However, there are multiple elements in common that provide enough correlation to propose a standardized methodology to define the requirement list based on the client's needs, constraints, and context.

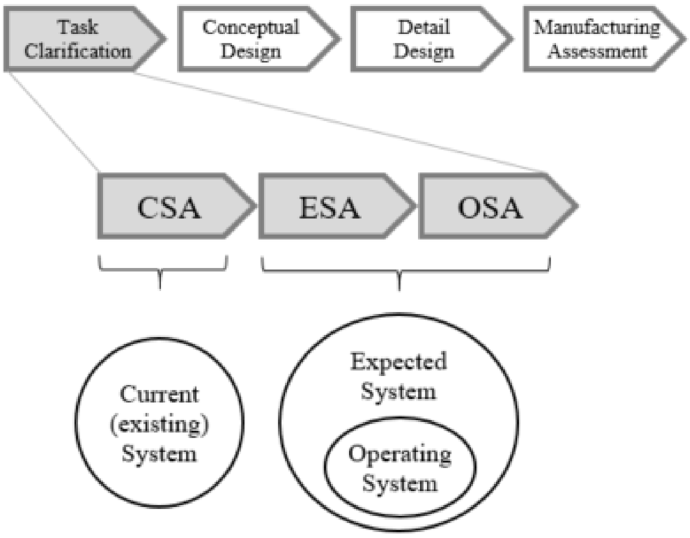

Figure 3.4. Task clarification subdivision.

The design project's success relies on the quantity and quality of the customer's information and the industrial environment. At the beginning of the project, the customers provide what they think is required to design the production system. However, most of the time, information is not complete or is not enough. That is why it is important to have general representation tools and methods to ensure that all the needed information is collected, represented, and exploitable. During task clarification, it is necessary to perform an exhaustive data collection guided and evaluated by the pertinent parameters. In the proposed approach, task clarification is divided into three steps: current system analysis (CSA), expected system analysis (ESA), and operating system analysis (OSA). Each of these steps addresses different stages of the system modeling to be designed, from the incomplete initial state (current system) to the identification of the properties of the ideal system (expected system), to finally, the definition of the required and attainable functions of the final system (operating system). Figure 3.4 shows the subdivision of task clarification and where the different systems are defined. It is important to mention that in the case of a new production system, without prior reference of an existing system, it is possible to skip the first step (CSA) and begin the method directly by the definition of the expected system, which will determine the boundaries of the final solution.

In the following subsections, each step of the task clarification phase is described emphasizing the objectives to be attained and their importance for formalizing the requirements list, the general context, and boundaries of the design problem.

- Current System Analysis (CSA)

The primary purpose of this step is to shape the current needs for the system. Considering the hypothesis that there is already a settled-up production system, the objective is to model functions and constraints to determine the client's needs in terms of time, cost and performance. Special consideration must be paid to the model's detail and complexity level because all data collected should be used in the subsequent phases.

The current system's components performing every activity and its interactions must be defined to identify the related needs in terms of time, cost, and performance. Firstly, the information is collected and modeled according to the granularity level shown in Table 3.1 (Component, Workstation, Production System, Organizational System, Business Model). Second, it is necessary to express customer requirements as exploitable values of time, cost, and performance. Third, position those requirements concerning one of the granularity levels.

Figure 3.5 shows the graphical formalism used to model the constituent elements of the system where the components are represented by grey rounded rectangles, Basic Functions by white rectangles, and the interaction time by the horizontal axis. Each interaction occurs in a time interval that corresponds to its duration and the interacting components. The customer's needs are defined for components and interactions. The criteria to evaluate these functions and interactions are expressed as requirements (type of parameter, target value, tolerance, control means). Moreover, that evaluation leads to implementing different KPIs that allow the consideration and integration of safety assessment tools or other aspects into the final solution.

Table 3.1 System granularity level

Granularity level	Entity A	Interaction	Interaction scope	Entity B
Business Model	Enterprise	Provide	Limitations/Purpose	Market
Organizational System	Site/Service	Provide	Limitations/Purpose	Site/service
Production System	Production line	Provide	Limitations/Purpose	Production line
Manufacturing System	Workstation	Provide	Limitations/Purpose	Workstation
Technical System	Technical component	Act with	Limitations/Purpose	Technical component

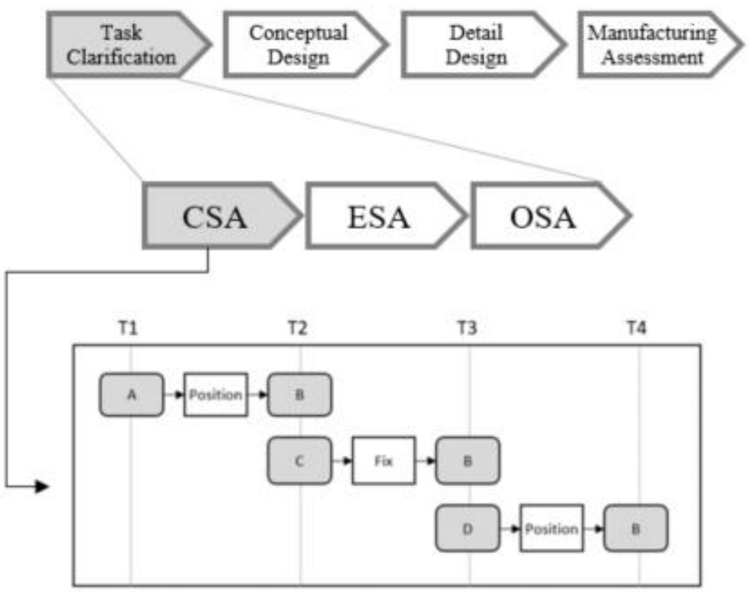

Figure 3.5. Interactions representation.

To validate the CSA is necessary to examine the completeness of the elements treated (activities, components, and interactions) connected with the studied activity. It is then essential to verify that the customer's needs are appropriately considered in the model's Basic Functions. Following this logic, it becomes necessary to check the adequacy, from a static and dynamic perspective, between the model and the actual system's structure. The cause-and-effect relationship between customer expectations and Basic Functions' definition becomes a key element to validate the step. To conclude this subsection, it is essential to highlight that CSA is the diagnosis of the system's current state, from which all the modifications and improvements will occur. Special attention needs to be put on this modeling level to avoid a waste of time and resources. In the next section, the characteristics of the ESA are explained based on the current system model.

- Expected System Analysis (ESA)

The Expected System's main goal is to define the boundaries of the Operating system inside the design problem context. Those boundaries provide the required information to the design team to develop a suitable solution for the client's needs. That is why the objective of this step is to define the ideal system that can meet the client's requirements. To define that system, it is necessary to identify the components, functions, and interactions to be removed or changed and identify those to be generated to fulfill the requirements. It must be done with the data collected at each level in the previous step. In a simple way, the goal is to make the design objectives set by the client flow onto the Basic Functions. Thus, they must be characterized through properties of the same nature as the design objectives. For that, each of them will be formalized in the form of a requirement defining the type of the property, the current value and the value to be reached, the associated tolerance, and the means of measurement (cf. Systems Engineering). That requires the identification, in terms of cost, time, and performance, of components and interactions that do not meet the customer's needs in their current state. Components and interactions are maintained if these features can evolve quickly to satisfy customer requirements (software updates, different settings). When these elements cannot evolve enough, they are replaced by new ones that suit the requirements.

To formalize and organize functions and interactions directly related to the customer's needs, specific parameters need to be defined: type of parameter, target value, tolerance, control means are expressed as requirements for all of them. Every element directly linked by the customer need is clearly distinguished by a color code in which green is a new element to be added, yellow is an item to be modified, and red is an element to be deleted. Based on these changes, the rearranging of the previous energy distribution, if it has been made, becomes necessary in a way that new dangerous situations for the workers can be detected. Figure 3.6 shows the representation of the expected system with the respective color code.

To ensure the relevance of possible solutions is necessary to compare the customer's needs with the current system. It is important to precise that there is no single solution, but rather a variety of solutions that will have to be sorted out using, for example, existing value analysis methods. That is to consider criteria that will determine the most fitting solutions for the design problem. In conclusion, the current system and expected system differences determine how far the final solution can go, based on its current state. The next step will begin a process of optimizing the already collected knowledge.

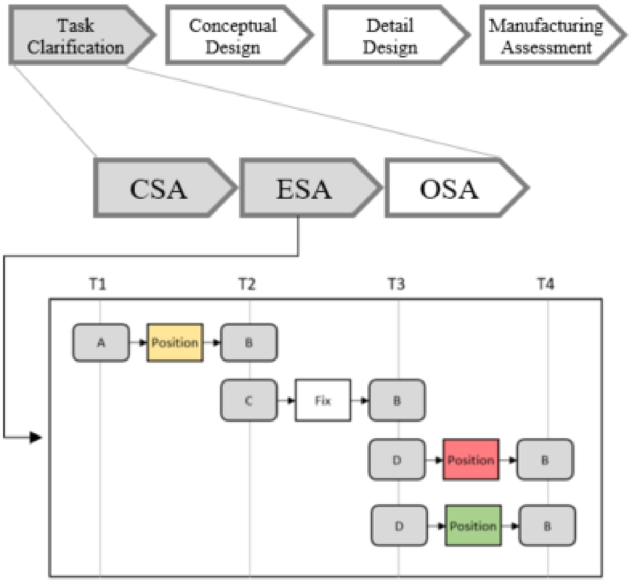

Figure 3.6. Representation of interaction modifications.

Operating System Analysis (OSA)

This step aims to define the required system based on the differences between the current and expected systems. The operating system is formed by new or modified components and interactions that satisfy customers' requirements. This description occurs in three moments, first in the operating system's mission, and its life cycle are specified. Then, the environmental stakeholders and Basic Functions are identified. Finally, connections between technical constraints related to stakeholders and Basic Functions are established to determine the extent to which they affect each other.

The mission has to be defined based on the expected result of the design process and the current system's modifications. An excellent starting point is to analyze the most time-consuming functions, cost the most, or perform the lowest. The operating system life cycle must also be defined and related to the needs of the customer. Standardizing how the mission is expressed is one of the critical features of formalizing the operating system. That can be accomplished by writing the mission in the form of an infinite verb and two complements that refer to time, cost, and performance requirements. The identification of stakeholders is made through a list of external elements that interact with the operating system components. The life cycle of the system is needed to define the nature and the reach of stakeholders. In Figure 3.7, a simplified version of the heuristic charts is shown, and all the diagrams that result at the end of the step.

The operating system's Basic Functions that ensure the mission's accomplishment are defined using its nature and perimeter. Different functional scenarios are considered, using the life cycle phases as a starting point and keeping stakeholders into account. A heuristic chart is also used as a representation method but with variations on the categories: mission, phases of life cycle, functional cases, Basic Functions, performance level, and characteristics. The expected output from every Basic Function must be represented in a manner exploitable by the designer. The expected system model must be reused to identify the elements and interactions that need to be created or modified. The expected system's configuration can be rearranged to define the configuration of the operating system. This model will take into account specific technical constraints and Basic Functions to fulfill the mission. The interaction characterization makes it possible to use safety factors to optimize the model from that perspective. Following this example, interactions that could pose a danger to one or more workers can be identified.

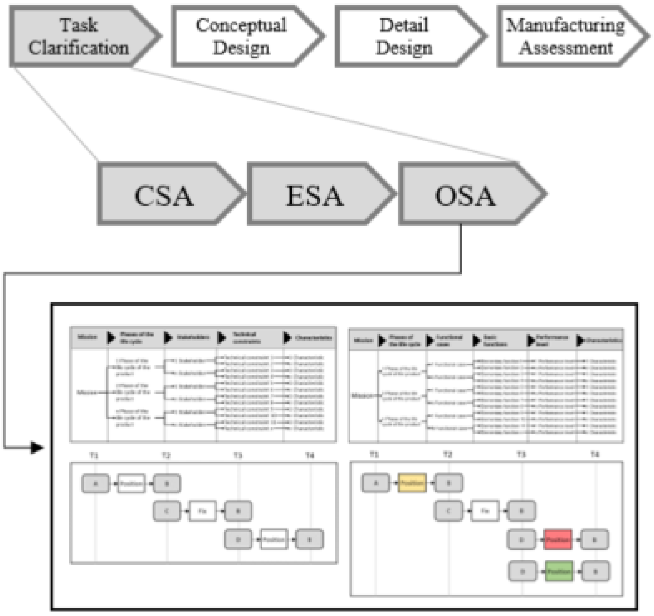

Figure 3.7. Heuristic charts of technical constraints and Basic Functions.

To conclude this section, it is essential to remember that the operating system is composed of the technical solutions necessary to comply with customer requirements defined in the two previous steps (CSA, ESA). This model is the starting point of conceptual design, so the operating system must be more comprehensive than the two previous systems. It is necessary to define two different types of functions that are explained in the following sections.

2.2 Conceptual Design

As stated by [Pahl & Beitz 2007], conceptual design is the stage of the design process in which the fundamental problems are identified through abstraction, function structures are established, appropriate working principles are identified and combined into a working structure, and the basic solution path is laid out through the elaboration of a solution principle. The purpose of the decisions made during this phase is to answer the following questions based on the requirements list agreed upon during task clarification:

- Has the task been clarified sufficiently to allow the development of a solution in the form of a design?
- Is a conceptual elaboration actually needed, or do known solutions permit direct progress to the embodiment and detail design phases?
- If the conceptual stage is indispensable, how and to what extent should it be developed systematically?

In the following subsection, the systematic approach of conceptual design proposed by [Pahl & Beitz 2007] is explained in more detail, as well as the main differences with the proposed approach of this research work.

2.2.1 Systematic approach

The conceptual design phase comes after task clarification. Figure 3.8 illustrates the stages proposed in the systematic design required to achieve the general objectives of the phase. Even industries and design studios have preconceptions and norms that, together with a desire to reduce risk, tend to delay better and more economical but unusual solutions. Customer, client, or product planning group may have included particular solutions in the requirements list. During the discussion of specific requirements, new ideas and new solutions may arise. Unconsciously, at least, certain solutions exist. Perhaps permanent concepts exist, and yet tangible concepts may be built upon them.

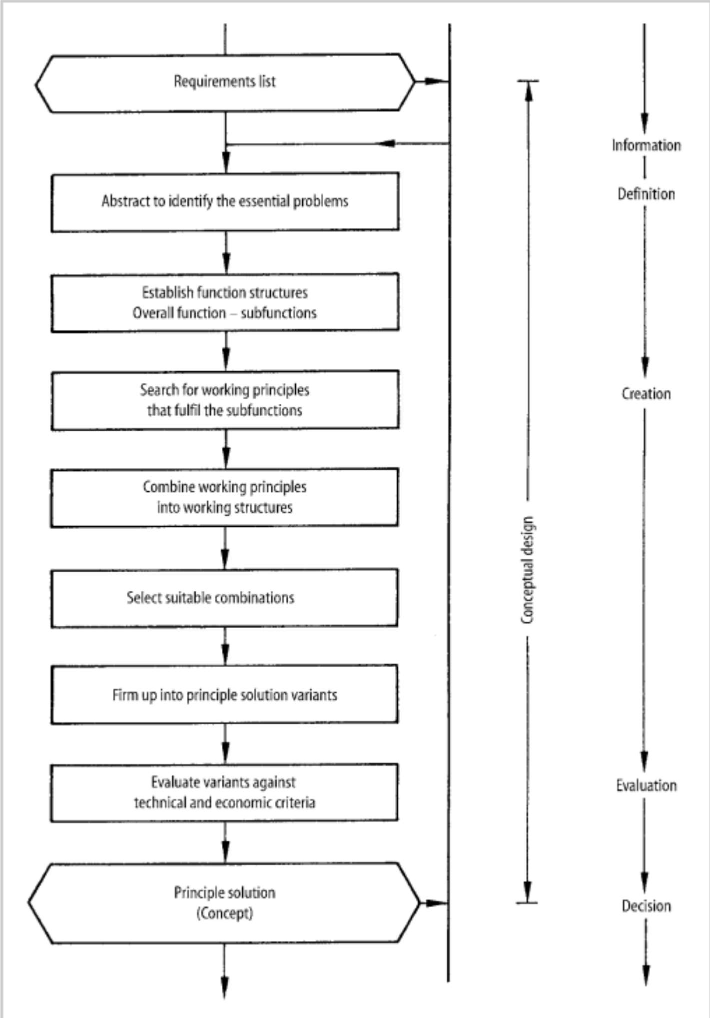

Figure 3.8. Steps of conceptual design proposed in systematic approach [Pahl and Beitz 2007].

<u>Abstracting to identify the essential problems</u>

Problems are more likely to be solved when new technology, techniques, materials, and fresh scientific discoveries are used. Every industry and design office is a repository of experiences, preconceptions, and customs that stand in the way of better and more economical but unorthodox solutions. The criteria list may have contained some particular recommendations for a solution. In addition, it is likely that during the debate of each criterion, a new solution may occur. Perhaps existing thoughts might be founded on fixed conceptions and false limits.

Designers must research for new and better solutions instead of just allowing themselves to be affected by fixed or customary concepts. Abstraction is employed to deal with focus and adherence to traditional thinking. The explanation oversimplifies the task at hand. When appropriately articulated, the general function and important restrictions become evident without prejudicing the choice of a particular solution.

Problems are solved more often when new technology, techniques, materials, and scientific discoveries are employed. To find better ways to respond, designers must hunt for better concepts that are still developing. Concretization is utilized to address attention and conventional thinking. Focused on the overall and ignoring the specific and incidental This causes the primary issue. A broad purpose and key limits can be discovered when they are stated clearly.

Establishing function structures

How intricate the problem is will determine how complicated the resultant overall function is. By complexity, it is implied that the linkages between inputs and outputs are relatively opaque, that the physical processes necessary are relatively complicated, and that the number of assemblies and components involved is quite extensive.

A complicated or overall function can be broken down into subfunctions of lower complexity, much as a technological system may be split into subsystems and elements. Individual subfunctions are combined to form a function structure that represents the overall function.

The goal of breaking down complex functions is to find subfunctions that will help with the future search for solutions and then merge these subfunctions into a simple and clear function structure.

The optimal way to break down an overall function, that is, the number of subfunctions and subfunctions per level, is found through the function's originality and search for solutions. With original designs, neither the subfunctions nor their interconnections are commonly recognized. Conceptual design's most significant tasks are to find the most appropriate design solution and develop the best design structure. An adaptable design's structure is well-known, and because of that, a particular function structure may be developed by analyzing the current product. This function structure may be varied by altering, adding, or excluding individual subfunctions or adjusting the way they are integrated.

Searching for working principles

Working principles for the various subfunctions must be identified, and these principles must then be merged into a working structure. Concretizing the functioning framework will yield the fundamental solution. A function principle must show how the physical function is carried out and how it is constructed and made up. Looking for novel physical effects is often unnecessary because design (geometry and materials) is the main difficulty. More importantly, it is difficult to draw a clear conceptual separation between the physical effect and the form design aspects. Work principles are often gathered along with the physical process, geometric and material features and synthesized into an applicable structure. Essentially, these theoretical notions are communicated through diagrams or freehand illustrations.

The solution field considered is meant to lead to several solution variations, i.e., several possible solutions. To develop a solution field, alter the physical impacts and the form design aspects. Additionally, each subfunction might be satisfied by many function carriers, with various physical consequences each.

The working principles research for subfunctions should be based on the following guidelines:

- Main subfunctions should receive preference, as the overall solution lacks a principle that has yet to be identified.

- Identifiable linkages between the energy, material, signal fluxes, or connected systems should be used to classify parameters and criteria.
- The operating principle should be determined from physical phenomena and, for instance, from the sort of energy. The best form design aspects for the physical effect should be selected and changed to suit the requirement.
- Also, based on these standards, break down, restrict, or generalize more.
- Property workpiece(s) preparation to assist in the process selection

Combining working principles

The primary challenge with combinatorial approaches is guaranteeing physical and geometrical compatibility of the working principles to be combined, ensuring a smooth flow of energy, material, and communications. Another issue is deciding which combinations are technically and economically advantageous from the vast number of potentially feasible combinations.

Working principles whose properties can be quantified are the only ones that can be combined using mathematical methods. That, however, is rarely possible at this level. Variant designs and control system designs, such as those involving electrical or hydraulic components, are examples of where this is conceivable. To summarize:

- Only combine subfunctions that are compatible.
- Only seek options that match the requirements list's expectations and appear to be within the given budget.
- Focus on the most promising combinations and explain why they should be chosen over the others.

Selecting suitable working structures

The solution field should be as broad as possible for the systematic approach. Designers consider all the classifying criteria and attributes to yield more options. The profusion is an inherent part of the systematic method. The theoretically allowable, but practically unobtainable, number of answers needs to be lowered immediately. However, a primary objective of any change should be to preserve effective functioning principles and not eradicate them. A structured and verifiable selection technique reduces the probability of selecting non-promising solutions from an abundance of ideas.

It consists of two steps: removal and preference. All bad ideas are removed from the outset. Preference should be given to options that are visibly better than the rest. Only these ideas are considered in the end-of-concept design phase.

According to the systematic approach, a designer should create a selection chart when presented with many solution options. In theory, at every phase, the only solution proposals pursued should:

- Be compatible with the overall task and with one another (Criterion A).
- Fulfill the demands of the requirements list (Criterion B).
- Be realizable in respect of performance and layout (Criterion C).

- Be expected to be within allowable costs (Criterion D).

Unsuitable solutions are rejected in accordance with the following four criteria. A and B are suitable for yes/no decisions and have few complications when used. When criteria A and B have been met, qualitative criteria (C and D) must be employed.

Criteria C and D, as quantitative factors, may lead to the exclusion of viable solutions as well as those that exceed the requirements by an unnecessary margin.

Firming Up into Principle Solution Variants

The principles already outlined are frequently insufficiently concrete to lead to the adoption of a specific paradigm. Since the search for a solution is based on the function structure, it is targeted, first and foremost, at achieving a technological function. Concept versions must be finalized before they can be examined, and this usually involves a great deal of labor. Selection process analysis may have previously discovered serious gaps in knowledge on crucial features, at times to the point where no meaningful judgment or judgment is conceivable. The qualitative and quantitative definitions of the suggested principles' most important properties must first be provided. The working principle, the embodiment, and task-specific limitations all have to be understood at least approximately. Only valuable combinations require more research. Another or a third method should be used if more information is required.

- The required information is primarily gathered using approaches such as:
- Rough calculations based on a set of assumptions.
- Rough sketches or scale drawings of potential layouts, forms, space needs, and compatibility.
- Preliminary experiments or model testing are used to determine the primary properties or provide approximate quantitative assertions about performance and optimization potential.
- The creation of models to aid in the analysis and visualization of data (for example, kinematic models).
- Analog modeling and systems simulation, frequently with the use of computers; for example, hydraulic system stability and loss studies utilizing electrical analogies.
- Additional patent and literature searches with more specific goals.
- Market research on suggested technologies, materials, and purchased parts, among other things.

With this new information, it is possible to solidify the most promising principles pairings to the point where they may be examined.

Evaluating Principle Solution Variants

The potential solutions that emerge from the selection process usually need to be consolidated before a final assessment is performed using more specific and maybe quantifiable criteria. This assessment considers technical, safety, environmental, and economic factors. To this end, evaluation processes have been created that can be used to assess both technical and nontechnical systems and can be employed throughout the product development process. Because evaluation processes are more involved than selection methods, they are only used to establish a solution's present value at the end of the major working processes. That usually happens when the designer is getting ready to make a big decision on the direction of a solution path toward the end of the conceptual design process. For evaluating principle solution variants, the following steps are recommended.

1. Identifying Evaluation Criteria.
2. Weighting the Evaluation Criteria.
3. Compiling Parameters.
4. Assessing Values.
5. Determining Overall Value.
6. Comparing Concept Variants.
7. Estimating Evaluation Uncertainties.
8. Searching for Weak Spots.

2.2.2 Proposed approach

This subsection describes the second design phase conceptual design phase of the proposed approach. During this phase, the introduction of energy flows for interactions between elements becomes necessary to find technical solutions based on energy transport, storage, and conversion. The conceptual design's main objective is to narrow down possible technical solutions based on the general model already defined. Figure 3.9 shows the subdivision of conceptual design where the operating system is fully defined.

Considering the type of energy required for a specific function and the type of energy available, it is possible to choose the most suitable solution in terms of cost, performance, and safety (see Chapter 5). The expected result of this phase is a conceptual model of the system with technical solutions already defined. This phase is also divided into three steps: Automatic Characterization, Energetic Characterization, and Components Selection. To ease the transition between functional and organic architecture, it is necessary to decompose the Basic Functions into subfunctions based on a behavioral model.

The first step comprises the identification of Basic Functions that execute the same nature activities and could be executed by multiple components, as well as the identification of the subfunctions needed to ensure proper performance. The second step is intended to decompose each subfunction into a combination of technical functions characterized by energy transformations. This characterization of basic energy manipulations and treatment allows to map energy flows inside the system and identify the system’s behavior. Finally, the last step defines the operating system elements that execute the Basic Functions based on energy treatment. It is simply a matter of substituting each Energetic Technical Function with a component having identical energy characteristics. In the following sections, the principal elements of the phase are explained.

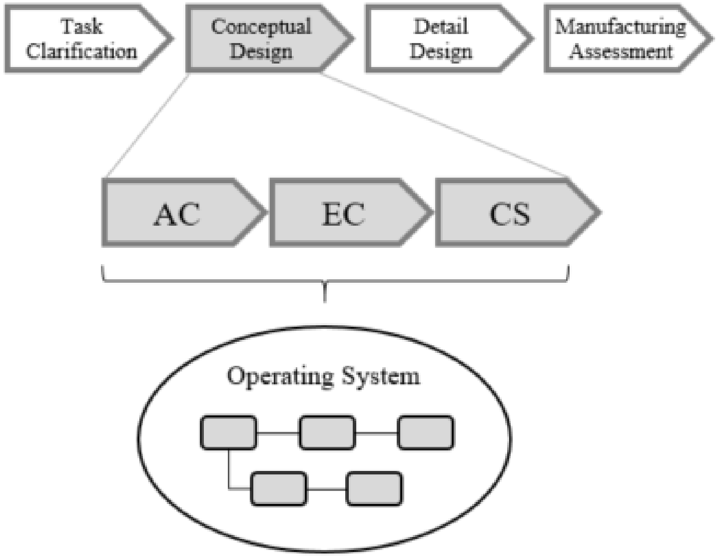

Figure 3.9. Conceptual design subdivision.

Automatic characterization

To control, command, and supply energy to the Basic Functions and achieve the expected result, defining a different set of functions specific to those tasks is necessary. Those functions are Automatic Technical Functions (ATF) needed to ensure Basic Functions performance and complement the system's functional architecture. The goal is to identify ATF's for every Basic Function from predefined categories. This classification simplifies the transition between the functional and organic architecture for the following steps. There are four types of ATF:

- Control: determines the deviation between expected output and measurement.
- Command: determines the signal to send to components based on the deviation between the expected output and the measurement.
- Energy Supply: provides energy to components to execute basic or technical functions.
- Action: uses the system's energy to execute Basic Functions.

ATF's structure must be described through interactions between functions. Any Basic Function needs energy supply elements, action components to execute Basic Functions, command devices, and control means. From a system point of view, these categories become subsystems of energy supply, action, control, and command necessary to carry on any internal or external function. The ATF modeling is made through a diagram that shows all the functions' links and interactions. This representation is a generic model that applies to all Basic Functions and exposes the operating system's graphical internal structure even if technical solutions or components have not already been chosen. ATF can represent a single component or a set of components that execute a specific system function. The ATF model is part of the interpreted world, but it introduces elements linked to the external world to define the final solution. Figure 3.10 shows a part of a model where three Basic Functions are represented: position parts, fix parts, and release parts. As seen, the sequencing of every action ATF triggers the control ATF of the following Basic Function, allowing the system to perform its intended mission.

This section has added to the general model of the operating system a new level of arrangement that allows a better understanding of the system's internal interactions from different granularity levels. However, from this model, it is not yet evident how to choose components or technical solutions that meet the requirements; that is why another set of technical functions must be proposed to finally complete the conceptual design, as explained in the following section.

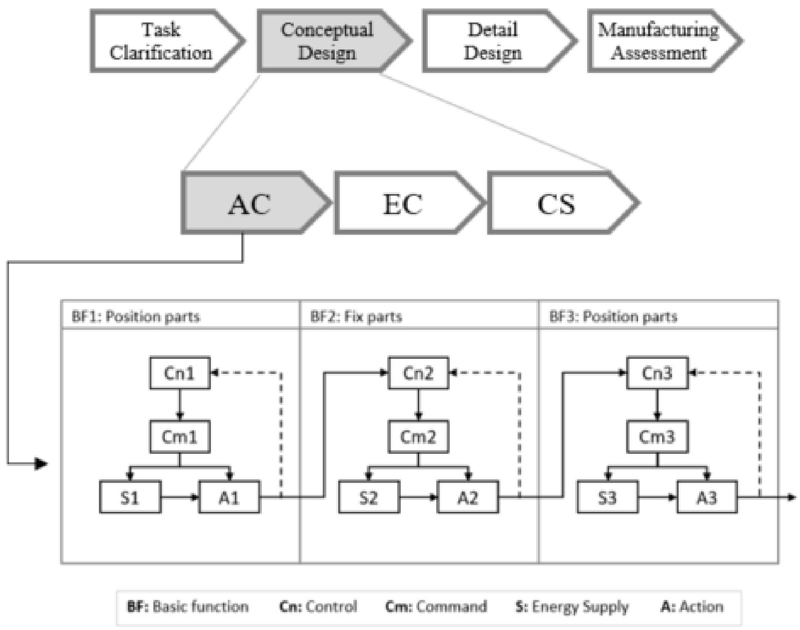

Figure 3.10. Automatic characterization model.

Energetic characterization

To define and model the organic architecture of the system, it is essential to define its behavior. This step aims to model the system's behavior through the treatment of energy flow inside the system, which can also provide the information needed for a safety assessment. That treatment has been defined as a set of Energetic Technical Functions (ETF) needed to attain the expected Basic Functions results from an energetic perspective. ETFs are actions that transport, convert or transform energy inside the system. They are the characterization of functions in terms of energy manipulation and treatment. That is why energy distribution needs to be identified based on the ATFs defined in the previous step. ETFs are determined by the different energy flows that exist inside the system. There are three types of ETF:

- Transfer: guides and moves an energy flow from a given point to another.
- Conversion: changes the nature and properties of an energy flow.
- Transformation: changes the properties of an energy flow without changing its nature.

Energy transfer, conversion, and transformation are the functions that system components have to execute depending on the type of input and output energy they get. It is crucial to identify the nature and the perimeter of these energy flows to characterize the components' behavior that will execute a given function. The first activity of this step is to identify the input and output energy flow of the Basic Functions that are already grouped as ATF. So, it is necessary to identify the type and nature of the different energy flows. These characteristics determine the type of manipulation that is required for a specific function. Based on the type of energy flow that goes through a function, it is possible to determine what kind of ETF is needed to ensure a proper energy treatment. The application method defines the possible type of energy processing that the function must perform: transfer, convert or transform (the elements to consider for the energy-based system modeling are explained in Chapter 4).

Figure 3.11 illustrates a Basic Function with every input and output energy flow. All ETFs must show the interactions with the others to detect all the energy distribution inside the system. This distribution can be used to determine safety or environmental risk during optimization and validation activities.

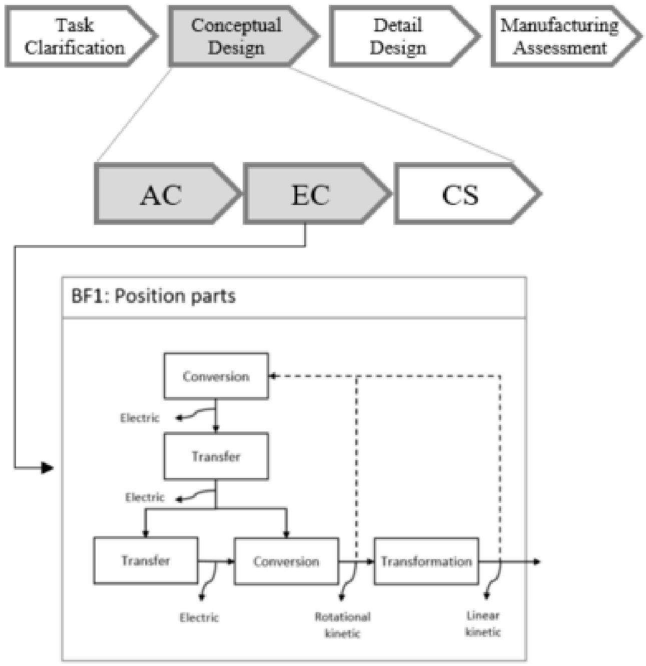

Figure 3.11. Energetic characterization model.

In this example, two functions of transfer, two of conversion and one transformation, are required to accomplish the Basic Function's intended behavior. The energy flow characterization allows identifying potentially dangerous situations related to the proximity of these flows to a hypothetical worker in the system. Based on the quantity, exposure time, and proximity of these energy flows and sources, a level of risk can be established.

All the components that do not exist in the current system need to be defined using ETF. These energetic functions are the input value to a set of technical solutions classified based on the type of energetic manipulation. There will be standard components that will not need any definition steps, but other components need to be dimensioned during the detail design phase.

This subchapter has shown the proposed system modeling process that is supported by the defined design framework. The procedural application of Energetic Characterization is explained in more detail and illustrated in Chapter 5. This way, it is possible to have a structured and organized design project that considers all the design phases, giving the designer the tools needed to address any design problem. This approach's contribution relies on identifying the client's real needs based on the current state of the production system and the definition of components based on an energetic approach using the functions' behavior, energy flow through components structure.

Components selection

The selection of components is the final step of the phase in which the organic architecture of the final solution is completed. In this step, the requirements defined during Task Clarification become the final criteria to evaluate the suitability of a component to accomplish a required function. That selection is made using ETFs and standardized catalogs classified by energy treatment. There are two categories of components: standard and specific. The first ones can be directly selected from catalogs proposing a classification by energy characteristics. As soon as this work is done, they will be fully known (performance, geometry, cost). As for the latter, they will continue the design process until the end. For specific components that have not been standardized, it is necessary to define all its parameters. That is why it is always preferable to choose a standardized component. First is necessary to identify the components available to complete the mission from the ETFs list. Then, define those components' nature and perimeter using the energy flows. With the energy treatment necessary to perform the basic and technical functions, it is possible to choose from catalogs the components that meet these functions by prioritizing incoming energy types that are more easily accessible in the workspace. A simple schematic diagram could be used to model the system operating with the resources and components chosen in the previous steps. Figure 3.12 shows the component's model based on the ETF characterization made in the previous step. As explained, one component is selected to perform the energy treatment needed to achieve the Basic Function on a first level and the mission on the system's level. For example, to convert the electric energy flow into a linear kinetic energy flow, two steps are needed, one conversion performed by the electric motor and one of transformation performed by the conveyor belt.

To evaluate and optimize the model, it is necessary to compare its behavior, functions, and results with the mission. It is important to compare it with the operating system model to find improvement points compared to the expected behavior. The objective is to control the relevance of the data related to these components (content and form) to validate the step's results by checking that the chosen resources and components are appropriate for the mission.

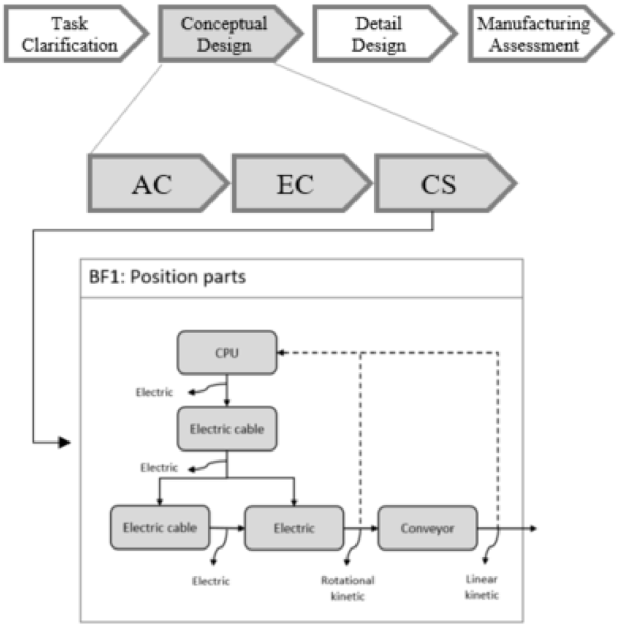

Figure 3.12. Components model.

This section has shown the first two phases of the proposed model supported by the design framework proposed by systematic design [Pahl & Beitz 2007]. It has shown that the sequence of treatment of the study objects is proposed logically and systematically. Nevertheless, even if the method becomes systematic, it does not set aside the characteristics of the final solution.

To complement the definition of each of the previous steps described in this section, it is necessary to propose a consecutive set of activities that ensures the accomplishment of the intermediate objectives and adaptable enough to be applied on every one of those steps and robust enough to provide valid and reliable results. Based on those requirements, a set of design reasoning activities is proposed and explained in the following section.

3. Design reasoning activities

As seen in chapter 2, Design for Six-Sigma provides a set of design reasoning activities that can be applied iteratively to different design problems to define and achieve specific objectives. The nature of these activities allows to integrate them in the specific case of this research work to apply the design steps proposed in the previous section. The design reasoning process must be sequential and logical, and it must be guided by a set of predefined, generic, and iterative activities that make it possible to achieve a specific goal. The definition of activities considered by [Antony & Coronado 2002; De Feo 2002] is suitable for adding to the proposed general framework. As pointed out by [El-Haik 2005], these activities will reduce the possibility of redoing all the project phases due to non-conformity validating every intermediate objective. Five generic activities are proposed: specify, design, model, assess and optimize, and Validate. These activities are used multiple times to achieve the intermediate objectives needed to validate their results.

3.1 Specify

In Specify, the objective is to define the information needed as input for the following activities. This information is obtained from previous steps of the project or the customer and the design environment. To specify this information, it is necessary to set expected results or objectives to achieve after treating that information. These objectives can be described in terms of target values or a list of required information related to the system's characteristics and properties, such as the ones proposed on CPM [Weber et al. 2003; Weber 2005, 2009]. Characteristics describe the system's structure, shape, and consistency that the designer can affect directly. Properties describe the system's behavior, but it cannot be affected directly by the designer; it can only be affected indirectly by changing the characteristics.

As an iterative activity, specify addresses different concepts along the design process. During task clarification, those concepts are related to identifying the client’s real needs. On the other hand, those concepts are directly linked to the technical characteristics needed to meet the client’s requirements during conceptual design. Those concepts need to be translated into exploitable information for the system development, as follows:

Consumer expectations: This activity is responsible for defining and prioritizing customer expectations and usage patterns concerning corporate, regulatory, and other internal company requirements. The emphasis here is on developing a deeper understanding of customers by allowing all design team members to learn through meaningful, direct customer interactions.

Customer interactions: This is typically accomplished by system and process planning teams, as well as a market research professional. It begins by brainstorming all of the design's conceivable consumer segments. Group the hypothesized possible client segments using the affinity diagram method. The final result is a classification of markets, user types, or system/process application categories. The design team should work from these categories to develop a list of clearly defined client groups from which individuals can be picked.

Customer expected design: The notion of "ideal" design is arrived at by synthesizing information gathered from constant monitoring of consumer trends, competitive benchmarking, customer satisfaction, and dissatisfaction surveys into an initial description of an ideal design. That will help in identifying areas for additional research and allocating resources appropriately. The design should be defined from the customer's perspective and should provide an initial glimpse of what an excellent design might be. This definition of customer-oriented ideal design will be illustrated using concept methods such as TRIZ (e.g., ideal ultimate result) and Axiomatic Design (e.g., axiom 1), both of which are effective tools for assessing consumer appeal and areas of likes and dislikes.

Customer satisfaction attributes: Attributes are potential benefits that a customer may gain from a design and are quantifiable. Each attribute is ranked according to the customer's perceived importance. This ranking is determined by the degree to which customers are satisfied with similar design entities incorporating that attribute (incremental design case). Robert Klein created a methodology for data characterization that [Cohen 1995] cites. Klein describes two methods for determining the relevance of client desires and needs: directly or inferentially from other data. The direct way of determining the relevance of an attribute is referred to as "stated" importance. The method for determining significance is based on how strongly satisfaction with a particular quality correlates with overall design satisfaction. The relevance of an attribute as determined by this indirect method is referred to as "revealed" importance. The Klein model classifies client desires and demands into four quadrants based on the relative relevance of each attribute (Figure 3.13). This analysis indicates the critical customer satisfaction aspects that should be investigated further.

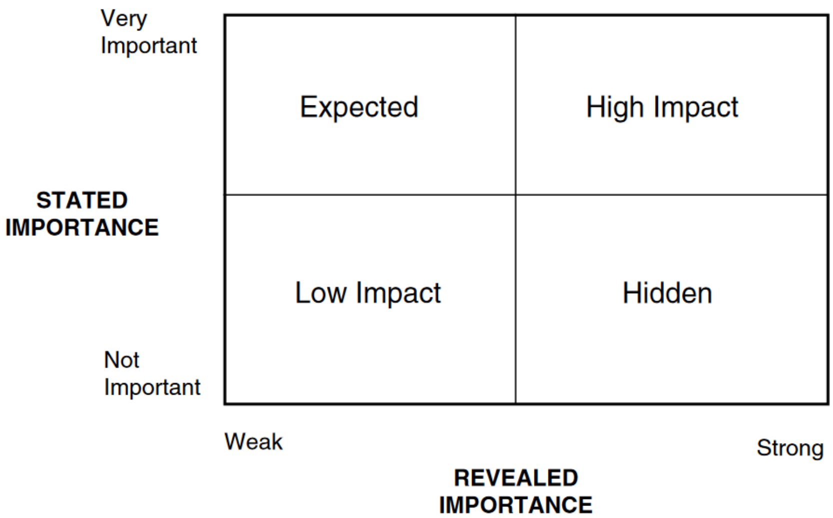

Figure 3.13. Klein model for customer satisfaction.

Refinement of client's needs: The goal is to fine-tune and prioritize the desires and needs of the customers. All consumer and legal requirements, as well as social and environmental expectations, should be included in the list of consumer qualities. To understand what can be standardized (universally) and what needs to be adapted, it is vital to grasp requirements and prioritize similarities and differences (locally). For each defined market group, customer traits as well as social, environmental, and other company desires can be refined in a matrix structure. In quality function deployment literature, these desires are referred to as the WHAT. The consumer significance rating, gained through direct or indirect engagement forms with the customer, is the primary motivator for allocating priorities from both the customer and business viewpoints.

3.2 Design

In design, the objective is to use the collected information to design general concepts for the objective proposed previously. This design refers to the fact of creating new information or knowledge using preliminary data. In this step, the concepts or elements are not fully defined but provide solid ground for the following activities. The previous concepts are structured to create a fully defined representation of the concepts or elements during the activity model. Depending on the intermediate objective and the elements manipulated, different models can be used, for example, a relationship matrix to relate Basic Functions with technical constraints or a sequence graph that shows interactions between elements during a time. Considering the two types of relations proposed by Weber in CPM, analysis and synthesis, the nature of the relations between elements will depend on the study object in the proposed method's model activity. The current system relations emerge from an analysis process of known characteristics, while the ones from the operating system are derived from a synthesis process, having in between the expected system that is a mix of both.

Based on Design for Six-Sigma, there are three methods for arriving at the most suitable concept design or process solution entity are (1) Axiomatic Design [Suh 1990, 2001], (2) TRIZ methodology [Ilevbare et al. 2013], and (3) Dr. Stuart Pugh's method of controlled convergence [Pugh 1991]. Controlled convergence is a solution iterative selection technique that allows the team to experience alternative convergent (analytical) and divergent (synthetic) thinking. The approach alternates between operations of generation and selection (Figure 3.14). The following enhancements to the controlled convergence method are suggested:

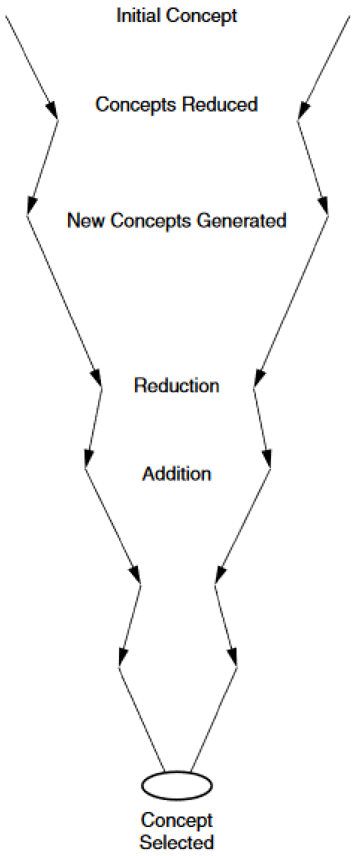

Figure 3.14. Controlled convergence method [Pugh 1991].

1. The "generation" activity can be enriched by applying the design axiom 1 and its derived theoretical framework, emphasizing the independence of functional requirements. This deployment will be strengthened further by a variety of TRIZ approach approaches that will be used to address design vulnerabilities where relevant.

2. The "selection" action can be aided by the use of axiom 2, which emphasizes the importance of design simplicity.

The approach of controlled convergence compares each alternative solution item to a reference datum. A single solution entity's evaluation is more subjective than objective. However, the strategy opposes the promotion of subjective notions, hence promoting objectivity. The controlled convergence method avoids undesirable characteristics and eliminates weak concepts, allowing for the formation of new concepts. It identifies the optimal solution entity as the one that is most likely to satisfy the customer's constraints and requirements as described in the design specification, as well as the one that is least susceptible to immediate competition.

3.3 Model

This activity is directly related to system modeling, which is the main subject of chapter 4. Nevertheless, in this sub section, a small introduction of the aspects to be considered is made. The first step in Model is to create the physical framework of the intermediate objects. The physical structure definition aims to serve as a catalyst for later concept and detail design work aimed at realizing this maximum potential. The axiomatic design method uses a zigzag pattern to create physical and process structures. The structure is mathematically represented by clustering matrices belonging to the same hierarchical level. The hierarchy is constructed by deconstructing the design into a series of simpler functional design matrices that collectively satisfy the functional requirements. The array of FRs should be inspected for independence, that is, to ensure that they are separate and unique from one another. For example, speed and torque are functional requirements that are independent of one another, albeit physics binds them. This requirement is necessary because it establishes a minimal array for design purposes capable of meeting design requirements. The client may not request additional functional requirements, resulting in overdesign or a suboptimal value proposition for the client.

During the early design phases, specific information is needed to evaluate particular parameters defined by the customer and the client. Those parameters change depending on the design project's goal, and it is essential to be able to identify the required information as part of the design process. For example, one goal is to provide a suitable integration of human safety in the early design phases for this study. In the literature review, some studies have used energy flow for the safety assessment of production systems. That is why energy-based modeling has been chosen to characterize a system's behavior. The use of energy provides enough information to define the system's organic architecture and a solid base to perform safety evaluations. The application of Behavior-Energy-Structure (BES) is made through Energetic Technical Functions (ETF) that appear in the second phase of the method using the gathered information during Task Clarification. However, this approach is represented along all the modeling activities using the three concepts discussed in the literature review. The logic sequence allows to fully define a system model based on its functions, behavior, and structure.

The introduction of ETF to the system modeling allows the designer to have a clear perspective of all the energy manipulations that the system executes and how they add to the overall production process. Based on this, it is possible to characterize the technical solutions needed to ensure each Basic Function. In conclusion, these concepts allow to complete the system model with three topological levels, interactions (Basic Functions), type of action (Automatic Technical Functions), and energy distribution (Energetic Technical Functions). The details of the modeling using BES are fully explained in Chapter 4. Identifying these elements is closely linked to the study objects proposed in the method and are explained in the next chapter.

3.4 Evaluate and Optimize

Evaluate and Optimize is necessary to reduce iterations of the design process because it progressively improves each aspect of the final solution along with its development. Also, this activity makes it possible to introduce different criteria, such as safety factors. The objective of evaluating and optimizing is to go over the list of design requirements and compare them to the final solution's results. Additionally, an importance index should be included for each item in the list. For instance, in vehicle or airplane design, any need relating to safety should be given a very high priority ranking. The following is a checklist of design needs for the various requirements:

- Data collection. The design data should be available from the design and development teams and the engineering department during the concept and detailed design stages. Additionally, data may be gathered through prior experience, competitors' present capabilities, a knowledge base, or client surveys.
- Required level of detail. The more specific the information, the better. Numerical goal values and numerical specifications are highly desirable for significant functional performance requirements. There may be a hierarchy of functional performance requirements in a complex system, including subsystems and component needs and specifications.
- A prioritized index. That is necessary. An itemized priority index is a ranking of a functional performance requirement's relative relevance. For instance, the "power output" need for an electric motor should be given a high priority index, as it is a fundamental primary functional performance requirement.
- Results of previous validations and knowledge base. That must be verified, and all pertinent information must be retrieved. It is needed to assess how much information from past validation findings and relevant data in the knowledge base may be used directly or indirectly in the validation process and how much extra information is needed to gather through new design analysis and testing to validate the requirement.

Design analysis [O'Connor 2001] is a collection of analytical techniques for analyzing design requirements, recommending design improvements, and validating or partially validating design requirements.

Numerous design analysis techniques exist. Design analysis methods can be broadly classified into three categories: design evaluation and review techniques, mathematical models, and computer simulation models.

Create methods for evaluation and review. QFD, FMEA, and formal design reviews are all instances of such procedures. All of these approaches include well-defined protocols and templates. They could assist team members through a thorough examination of the present design in detail to ascertain its strengths and faults. These methods are more system-oriented, exhaustive, and subjective than other approaches of design analysis. They rarely have the ability to give "solid" validation. Models derived from mathematics. The most frequently used mathematical models in design analysis are the following:

1. Mechanism-based mathematical models such as mechanical stress, strength-strain mathematical models; mathematical models for electrical voltage, current, and resistance; logical-mathematical models; financial mathematical models; mathematical models for three-dimensional geometric positions; and so on.

2. Statistical and mathematical software, such as Mathematica, Microsoft Excel, optimization software, and MINITAB. These techniques can be used to model and analyze designs ranging from simple to moderately complex. That can provide a reasonable level of validation capacity for some applications. A mathematical model, for example, can forecast the link between current, voltage, resistance, and other parameters. However, it rarely provides adequate validation for operational environment needs, reliability needs (in the absence of testing or computer simulation data; math alone cannot adequately validate dependability), and other needs.

3.5 Validate

The last step, validation, serves to approve the optimized model based on time, cost, and performance criteria or any other aspect that needs to be validated in the final solution. Design validation is a technique that confirms that optimized system and process designs execute at the level specified by the customer. The system's design must be verified in the following areas:

1. Validation of functional performance. That validates that the system is capable of meeting all of its functional criteria. For instance, functional performance validation on a television verifies that the television can receive television signals, make visually acceptable television images, and provide appropriate sound effects. Functional performance validation of a pipeline verifies that it can transport liquid at the specified volume within a specified period and that it can withstand fluid pressure, among other things.

2. Validation of operational environmental requirements. This test determines if the system can perform its function under a variety of environmental conditions, including extreme heat and cold, shocks and vibrations, humidity, wind, salt, and dust.

3. Validation of reliability criteria. This determines the system's ability to fulfill its tasks over a lengthy length of time. Numerous things are designed for prolonged use; for example, people anticipate a car to remain in reasonably excellent shape for at least seven years. This validation should encompass both usable life and functional degradation.

4. Validation of usage requirements. This validates the system's ability to perform its duties under a variety of different usage settings at times, abusive usage conditions. For instance, a copier manufacturer might conduct a test to determine whether the copier can still produce acceptable copies on smaller-size paper or thick or thin paper.

5. Validation of safety requirements. This validates that the system complies with all applicable safety regulations. For instance, a toy manufacturer would be required to ensure that the products they manufacture do not pose a harm to children. A bridge's capability to handle high wind, waves, stress, and fatigue should be checked to ensure that individuals crossing the bridge have no risk of mishaps.

6. Validation of interfaces and compatibility. If a component or piece of equipment is required to interact with another component or piece of equipment, it must ensure that they work correctly together (i.e., are compatible).

7. Validation of the need for maintainability. This determines whether the required maintenance work can be completed conveniently, how effectively the maintenance can "refresh" the system, the average time between maintenance, the mean corrective maintenance time, and the mean preventive maintenance time.

Not every system requires all of these validations. The validation needs and relative relevance of each type of validation activity will vary significantly between systems; a validation needs analysis should be undertaken to generate a list of all validation items.

4. Synthesis and integration

As it has been exposed in this chapter, the proposed method uses a modified version of the general design framework proposed in project-driven design theories [Pahl & Beitz 1996; Pahl et al. 2007], composed of four different phases: Task Clarification, Conceptual Design, Detail Design, and Manufacturing Assessment. The proposed phases and steps provide a well-structured design framework based on project-driven design and design reasoning that goes from the basic need to the final solution, allowing the designer to introduce decision-making tools related to specific expertise (human safety). The integration of design reasoning activities makes it possible to have a matrix-like representation of the design process, as seen in Figure 3.15. That proposed representation provides a logical sequencing for every decision needed to be made during design. The oscillating nature of the different activities to be followed by the design team provides all the required information to schedule the development of the design process. Using a Gant diagram to represent the duration of each step and the iterative design activities as reference makes it possible to completely define the project planning of the design problem. That is an approach that has not yet been explored in the literature and enriches current design theories, linking the general framework with basic design tasks.

Figure 3.15 shows the three elements that form the integrated framework: phases as horizontal arrows, steps as subdivisions of the phases, and the design reasoning activities as the vertical arrows on the left side. Every element of the matrix represents a basic design task that is sequenced by the project development's oscillating behavior. This matrix-like representation is proposed to identify basic design tasks that integrate the three points of view discussed in the literature review.

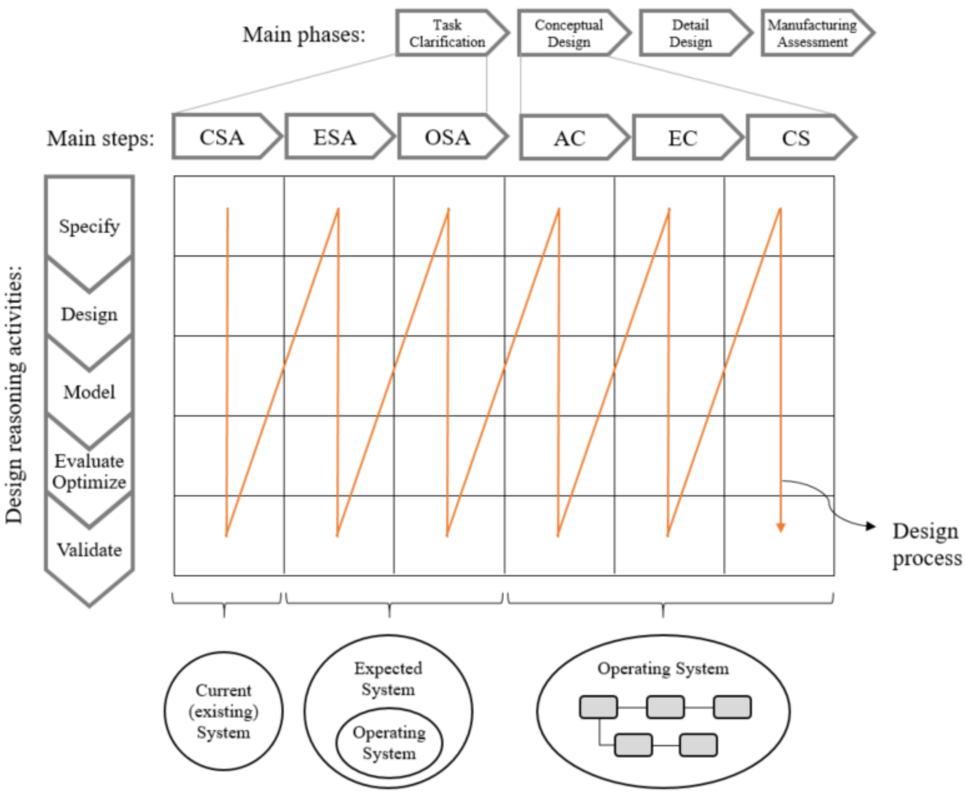

Figure 3.15. Integrated design framework.

Chapter 4: System modeling

Abstract

This chapter presents the main elements considered for the definition of the proposed system modeling. The interactions and exchanges between the operating and operated system are explained to understand the modeling of the final solution as a whole as well as its individual components. From the definition of the term system and its main characteristics and the system and product modeling approaches proposed in the literature review, multiple elements have been adapted to be part of a more robust design framework compatible with human factors and safety assessment. Those elements are explored in detail in this chapter to understand better the thought process involved in the definition of the proposed approach. The ontology of Function-Behavior-Structure (FBS) is explained in more detail. The Product-Service system modeling approach is introduced to understand the relation between the physical object performing a function and the final result of that action. The approach of Goal-Function-Behavior-Structure is explained as a parallel to FBS to highlighting the available and compatible tools for the proposed approach. Behavior-Energy-Structure is the developed model used to represent the system and its components. The definition of the three main aspects of the approach is explained as well as the relation between the system model and the design phases and steps.

1. Introduction

This chapter describes the elements considered to develop the proposed system modeling of the approach. The need to model the behavior of a system and its components demands the selection of representation tools. Based on the main objective of this research project and considering the most relevant elements from the literature review related to system modeling, energy flow has been chosen to characterize the system as a complement to its behavior and structure (BES model). This approach allows the definition of the system's general behavior and structure and expresses the common elements between design and safety assessment. BES is implemented by Energetic Technical Functions (ETF) that emerge in the second phase of the process utilizing the information gathered during Task Clarification. However, this methodology is reflected in all the modeling phases by integrating the different viewpoints of design found in the literature, which is necessary because it is a general model. In Figure 4.1, the progression of the system model follows the design steps to refine and complement it. The logic sequence allows a system model to be fully defined based on behavior, energy, and structure.

As shown in Chapter 3, depending on the changes required in the current system and defined in the expected system, the operating system is based on specific functions that define future system components. The operating system's general model must be achieved by choosing technical solutions. These solutions are chosen based on different energy flow manipulations within the system. Basic Functions (BF) interactions define the behavior and structure of the system. Then, the Automatic Technical Functions (ATF) define the link between the system’s behavior and energy flow, and then the Energetic Technical Functions (ETF) specify the system's structure based on the energy flow. ATFs also define the internal behavior of each BF. Thus, the ATFs allow a functional and organic decomposition of the system. The latter is pursued via the combination of ETFs. Those last two elements facilitate the transition from BFs to system components by regrouping functions executing the same actions. At the design level, energy is a common element in functional architecture (in the form of energy behavior) and organic architecture (in the form of energy transformation component). In the following sections, different elements considered for the definition of the proposed modeling are discussed, such as the concept of system and the different models used in design theory.

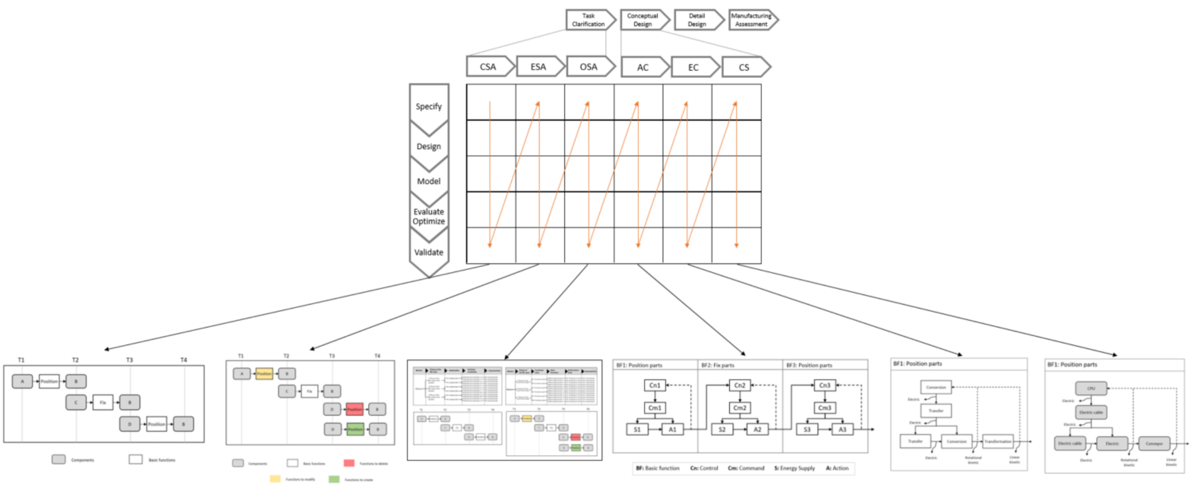

Figure 4.1. System model development.

2. The concept of System

The term system is used to represent groups of elements and interactions in an abstract way that makes them easier to understand. It is a good place to start when defining a design problem because it is solution-independent. A system is described as a collection of interacting elements structured to achieve one or more declared purposes [ISO/IEC 2008; INCOSE 2010]. When defining a system, three concepts must be considered: requirements, scope, and architecture [Faisandier 2011]. In terms of services and restrictions, requirements refer to the system's expected outputs, which are the principal result of the requirements definition. The scope of a system refers to its boundaries, what it includes, and how it interacts with the rest of the world. The term architecture refers to a system's operational and physical structure being clarified (i.e., components organization).

2.1 Requirements

As stated by [Ross & Schoman 1977], requirements specification must explain why a system is necessary, based on present or future circumstances, including internal operations or an external market. It must specify which system characteristics will be useful and satisfying in this situation. It also has to specify how the system will be built. When a factory needs a new production system to accommodate the manufacturing of a new set of products, it requires more than a new structure. It will require new Basic Functions to be performed by humans or machines, new technical functions to control, command, and supply energy to those Basic Functions, safety elements to protect nearby humans and machines, supply chains to be adapted to the new production system, the different phases of its life cycle, stakeholders and their impact on the system as well as the other way around. As a result, production systems design involves defining the requirements of the physical structure that will perform the mission, as well as defining the requirements of the system and its interactions with the surroundings. The main output is the information, which guides the design team in the definition of the system components. A structure comprises components that are needed to carry out Basic Functions, which enable functions to fulfill goals, which state the clients' needs depending on the context. As a result, the design team must first comprehend the context and how the clients intend to achieve their objectives to describe the system requirements. The system is distinctive due to its context, aims, and methods for achieving them. As a result, just copying and pasting current solutions will not suffice to meet clients' expectations. Figure 4.2 shows the area of interest for the requirements definition. In this case, both systems need to be considered. The operating system will dictate the technical requirements for the internal elements, and the operated system will dictate the requirements related to the impact from and to the external elements.

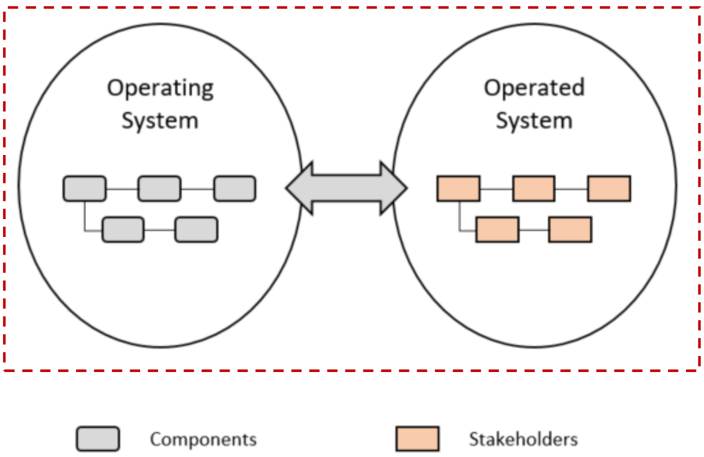

Figure 4.2. Area of interest for requirements definition.

2.2 Context

The first element to consider for a system is its context, needed to comprehend its surroundings. The context is represented by the environment in its current state (i.e., without the system). According to System Engineering, the environment is the surroundings (natural or artificial) in which the system-of-interest is utilized and supported; or in which the system is being developed, produced, or retired [INCOSE 2010]. The term environment is frequently substituted by domain in software engineering, particularly in the Problem Frames approach [Jackson & Zave 1993]. The notion of System Engineering is implicitly limited to physical items, but the concept of Domain is more expansive, encompassing intangible artifacts such as information or know-how. The following domains add to the concept of Environment: system independence, the larger nature of the environment, and a differentiation between the present and future state. In Software Engineering standards [IEEE 2010], some of these aspects are utilized to establish the idea of Environment. The term environment in this study is defined as a precise present context that includes all of the system's surroundings that will impact or be impacted by the system's existence, directly or indirectly. Any external factors or environmental factors (such as stakeholders, situations, conditions, and information) that exist independently of the system's existence are included in the surroundings. Those elements are grouped to form the operated system (Figure 4.3). That is the set of elements that interact directly with the Operating System, but the interest is not the interactions between the elements of the Operated System. However, those elements naturally limit the scope.

The environment in Value Management is made of existing artifacts known as external elements or interactive agents [AFNOR 1996]. The workers of the stations, the geometry of the building and access points, the managers and directors of the company, the numerous regulations and standards all contribute to the atmosphere of the factory and the production system. Each of these elements exists in its own right, independent of the operating system that defines it.

An external element (stakeholder) is a separate, already-existing item, whether physical or not, whose behavior or condition will influence or be influenced by the system directly or indirectly. All the components and functions required to satisfy the clients' requests define the scope of a system. In the development of a new production system, the system's elements are initially unknown (Figure 4.4), but then they are defined based on the requirements definition and functional process that responds to the system’s mission (system as a white box).

The terms "goal" and "function" are linked to the term "black box" system. Therefore, the transition from the "black box" to the "white box" is made by breaking down the mission into sequenced Basic Functions. Note that this decomposition is made from elements of the same nature (behaviors). Each function reflects an intermediate state of the Operated Stakeholder represented from the BES model. An external functional analysis (or functional analysis of needs) in Value Management corresponds to this viewpoint [AFNOR 1996].

A system is then a black box that represents a collection of structured and ordered (inter)dependent components (i.e., sub-systems) that work together to have an expected effect on their environment. To be reliant, each component must be designed, recruited, purchased, or created during the creation of the system.

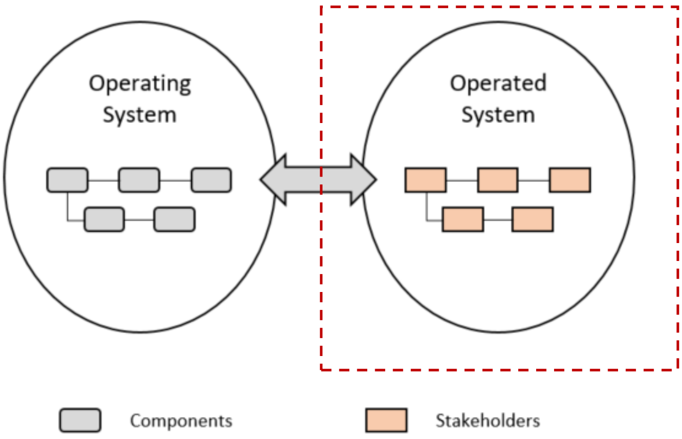

Figure 4.3. Area of interest for context definition.

Figure 4.4. System as a black box.

2.3 Architecture

The term architecture refers to a system's functional and physical structure being clarified (i.e., components organization). Figure 4.5 shows the area of interest for the architecture definition. In this case, the focus will be on the operating system, the internal elements physical attributes. A system is viewed as a white box (Figure 4.6) while working with its architecture, with all of its components visible and observable. As stated in the Value Management taxonomy, the components of a system are referred to as internal elements instead of external elements [AFNOR 1996]. Internal Element and Resource must still be distinguished. A resource in this study can be either internal or external to the system. Both terms allude to opposing yet complimentary points of view. The terms Internal and External Element refer to the overall system, whereas Resource is a physical component that may be called upon to respond partially or entirely to one or more functions of the Operating System. An internal element is any physical or nonphysical object whose existence depends entirely on the system's existence and contributes to its proper operation.

In a production system, a worker is an internal element required to carry out a specific task (for example, assembly, quality control, or storage). However, that task can also be performed by either a different worker or a machine. An internal element is the current individual or element that performs the task. In contrast, an external element is the replacement of that individual or element by a stakeholder capable of performing the same task without affecting the internal functioning of the operating system. To take it a step further, the current worker performing the task and the external element can be considered as the same component, but only the external element exists independently of the system.

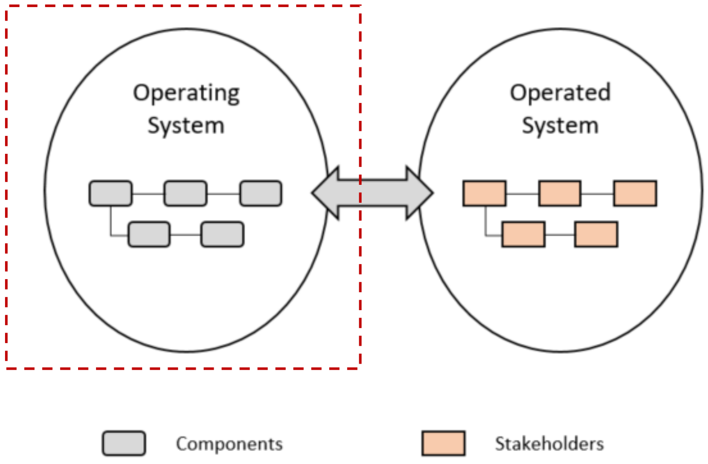

Figure 4.5. Area of interest for architecture definition.

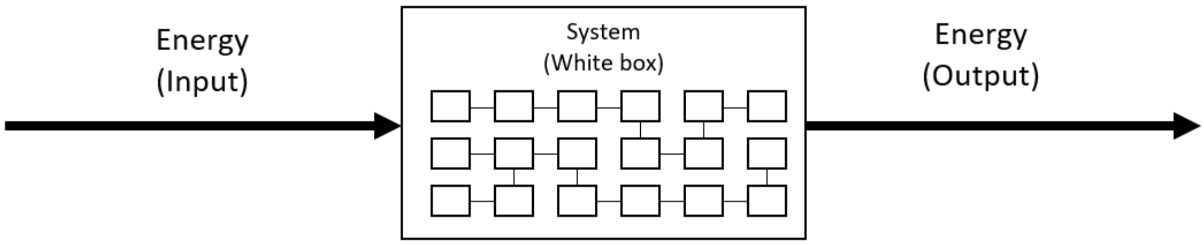

Figure 4.6. System as a white box.

When dealing with options, innovation, and changes, the importance of such distinction becomes apparent. The fact of calling upon external resources on a massive scale reduces the time and, therefore, the cost of development, but also the technical risk. In terms of innovation, technical innovation can be reduced, but not necessarily the originality of the system (it is possible to make a very innovative system only from standard components).

3. System models in design theory

Design theory models are applicable to a wide range of systems and disciplines. Engineering disciplines created design models based on the Vitruvian method [Le Masson et al. 2013]. Most of them, including Systematic Design [Pahl & Beitz 1996], Theory of Technical Systems [Hubka et al. 1987], FBS [Gero 1990], Axiomatic Design [Suh 1998], or C-K Theory [Hatchuel & Weil 2003], are primarily concerned with product and process systems.

In the early 1990s, the concept of service became popular [Goldstein et al. 2002]. Compared to Moritz's seven criteria [Moritz 2005], most services have three basic qualities: activity components rather than items, concurrent production-consumption, and customer involvement in the process [Karni & Kaner 2007]. Even if these characteristics can be debated, they provide insight into the gap between existent design theory models. The environment and the influence of mass production/consumption of artifacts are two of the most pressing industrial issues right now [Tomiyama 1997; Umeda et al. 2000]. The notion of Product-Service Systems (PSS) is one of the solutions identified: a business model shifts away from product ownership and toward selling usage and capability [Mont 2000]. A new engineering dubbed service engineering [Arai & Shimomura 2004] and a new design model more suited to such integrated systems results from the paradigm change from product and service systems to product-service systems. PSS techniques are currently lacking [Müller & Blessing 2007], and much more research is needed [Vasantha et al. 2012].

Existing design models refer to either the product or the briefing and project process. Gero's FBS approach was recognized as a viable framework for developing a requirements definition model through the construct of Behavior following a critical study of the definition domain and a comprehensive (but non-exhaustive) literature review on design methodologies and models. The Behavior construct incorporates the concept of product properties, which has yet to be integrated into the description of the proposed approach. A passive Behavior that can realize a Function is represented by a product property. It is an alternative to an Activity in the PSS construction system called an active Behavior. As a result, it is recommended to employ the Behavior construct to represent and facilitate function allocation to the product part via energy flow and treatment. In addition, the construct of Structure adds a conceptual dimension to the definition domain. The original FBS paradigm, the PSS model, and the GFBS approach are described in the next section before introducing the proposed system model of this research work.

3.1 FBS model

The situated FBS model [Gero & Kannengiesser, 2004] incorporates three classes of variables as the object of design activities and eight reference processes, as well as three types of contexts in which those processes can occur. The following are the reference variables:

- Functions (F) describe the object's goal, i.e., what it does.
- Structures (S) describe the object's components and relationships, i.e., what the object is.
- Behaviors (B) describe the attributes derived or expected to result from the object's structure (S) variables, i.e., what the object does.

These variables are created and altered by processes that occur in three distinct worlds that are recursively linked.

- The interpreted world is made up of sensory experiences, concepts, and interpreted representations of that world with which the designer interacts, while the external world is made up of representations outside the designer.
- The expected world is the one in which the designer's activities are imagined following existing goals and interpretations of the current state of affairs.

Figure 4.7 depicts the basic processes that result from the situational FBS model [Gero & Kannengiesser, 2004] and can be summarized as follows.

- Formulation is the process of interpreting explicit requirements (R) to develop an interpreted representation via the variables F^i, B^i, and S^i, and then focusing on the related subsets Fe^i, Be^i, and Se^i that make up the first design state space (Figure 4.7, Processes 1-10).
- Synthesis starts with the expected behavior Be^i and establishes the external representation of the artifact structure (S^e) (Figure 4.7, Processes 11, 12).
- The actual behavior (B^i) of the synthesized structure (S^e) is derived by analysis (processes 13, 14).
- To determine the design solution, evaluation compares the behavior resulting from the structure (B^i) with the expected (Be^i) behavior (process 15).

If the evaluation yields a positive outcome,

- The Documentation process (processes 12, 17, 18) provides a design description for manufacturing the artifact: whereas the FBS framework represented all documented information with a single type of variable D in its original form, the situated model distinguishes between three different classes of externally represented items, namely Se, Be, and Fe.

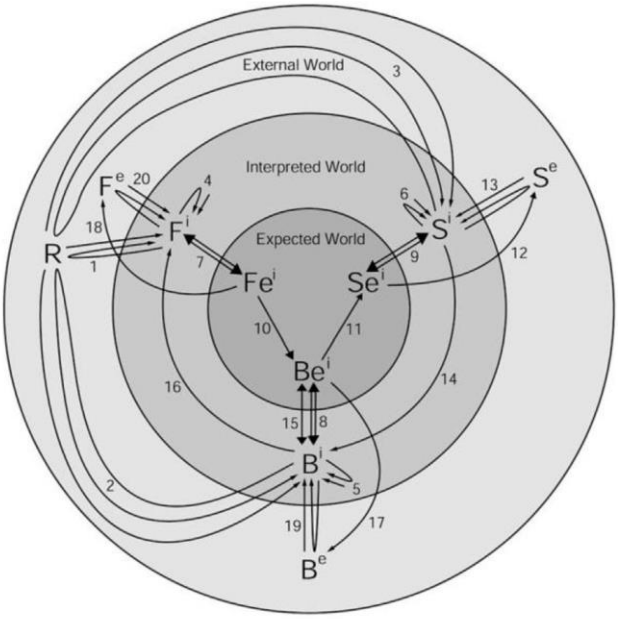

Figure 4.7. FBS framework [Gero & Kannengiesser 2004].

Furthermore, if the evaluation yields unfavorable results, the design process loops back to the previous steps, defining three basic loop-back processes that characterize the design's iterative nature.

- Type 1 reformulation (processes 6, 9, 13) deals with changes in the design task's structure variables.
- Type 2 reformulation (processes 5, 8, 14, 19) deals with changes in the behavior state space during the design phase.
- Type 3 reformulation (processes 4, 7, 16, and 20) addresses changes in the design state space in terms of function variable adjustments.

All of these reformulations contain specific basic sub-processes. By interpreting sensory experiences or concepts that make up the interpreted world, the sub-process of interpretation modifies variables observed in the external world. That is accomplished by push-pull processes, in which the ‘agent interacts with both its external (by interpretation) and internal (by constructive memory) environments' [Gero & Kannengiesser, 2004].

The concentrating process focuses on certain features of the interpreted world and uses them as goals in the expected world. When actions are suggested based on the expected world's goals, they should cause states (and thus changes) that fulfill those goals if they are carried out in the external world.

A major and minor issue that comprises this research's focal points emerges from a close examination of the model. The Identification of Needs and Requirements is the first (and most important) issue. The definitions are not entirely accurate. The requirements (R) of a design challenge are clearly mentioned by [Gero & Kannengiesser 2004]. However, they do not believe there is a distinction between Needs and Requirements. The requirements' statement appears overly basic compared to the detailed description of the following design processes, which is consistent with the little importance traditionally ascribed to user needs awareness in design theory. [Vermaas & Dorst 2007], for example, have acknowledged this deficiency. As a result, they introduce the concept of Purpose in addition to Behavior and Function.

In their contribution, a function is defined as a "physical disposition of an artifact that contributes to the reasons for which the artifact is designed," rather than "the consequence of the artifact behavior." Purpose, as it pertains to a customer, is defined as "anything that satisfies a need," indicating that the design process, in Vermaas and Dorst's minds, encompasses more than just translating some needs into functional specifications. Indeed, Gero has already looked at the term 'Purpose' and its links with Function in [Rosenman and Gero 1998], where the design process is depicted as beginning with a 'Purpose' (or intent). The design process begins with interpreting Function as a means of achieving a specific Purpose. While the research explores how Purpose conveys human utility values and its impact on FBS variable interpretation, the same concerns about a lack of differentiation between Needs and Requirements apply. Furthermore, the idea of Purpose was not ‘placed' in the subsequent research by Gero and associates; as a result, the current situated FBS model fails to describe the cognitive processes that occur or may occur while determining needs or developing requirements specifications.

The Formulation phase processes (Figure 4.7, processes 1-3) are irregular in the following sense compared to the processes 4-20 and represent a second minor issue. In the FBS model, there are two sorts of transitions: world changes and class changes.

- World change: variables (F, B, or S) change their reference world (i.e., External, Interpreted, or Expected); for example, in the focusing steps from F^i to Fe^i (Figure 4.7, process 7), B^i to Be^i (Figure 4.7, process 8) and S^i to Se^i (Figure 4.7, process 9);
- Class change: variables (F, B, or S) are produced from variables belonging to another class but still refer to the same world; (Figure 4.7, process 10).

The inconsistency now is that the processes 4-20 involve either a world change or a class change, whereas the formulation processes 1-3 involve both.

In reality, class transitions (transformations from one type of variable to another) are more likely to manifest as built-in sensory experiences, percepts, and concepts (i.e., in the interpreted world) than as envisioned outcomes of a designer's actions. World changes are also expected to manifest themselves through actions (from the expected to the external world), interpretations (from the external to the interpreted world), and focusing (between the external and the interpreted world). However, they are always linked to a specific type of variable (action on a variable, interpretation of a variable, or focusing on a variable).

The use of Requirements, which are referred to as something belonging to the External World, in the Formulation phase produces Interpreted Functions, variables Fi, Interpreted Behaviors, variables Bi, and Interpreted Structures, variables Si, which are variables of a different class and belong to a different world, namely the Interpreted Word. In other words, the only operation that requires both a change in the reference world and a change in the variable class is the transition from Requirements to the interpreted variables Fi, Bi, and Si.

It may be claimed that this irregularity conceals the original FBS model's oversimplification of the processes that may occur when a designer handles needs and requirements (Issue 1).

Since its initial conceptualization [Gero 1990], several papers have been written about Gero's Function-Behavior-Structure (FBS) framework; Gero has further developed and integrated this model [Gero & Kannengiesser 2004], and this interpretation is assumed to be the reference starting point in the current system modeling study. The scholarly debate surrounding the FBS framework has exposed some difficulties, such as the lack of a consistent definition of a function [Vermaas & Dorst 2007] and limitations in modeling human-machine interactions [Wang et al. 2002]. Nonetheless, the FBS model is still used to represent design processes and tasks as a reference model.

3.2 Product-service system modeling

The Product-Service System (PSS) is mainly discussed as a business model in the literature. Instead of selling items, it focuses on providing functionality or usages to consumers [Meier et al. 2010]. The goal is to provide a marketable combination of products and services that will simultaneously satisfy consumers' demands [Goedkoop et al. 1999] while also increasing the market proposition [Mont 2000] by merging services with traditional product capabilities [Baines et al. 2007].

Product-Service Systems (PSSs) are a concept that unifies the planning, development, and delivery of products and services across the whole life cycle. It is mainly employed in academia, but the industry is not familiar with it. Nonetheless, solutions that combine products and services are gaining popularity. Some suppliers consider themselves to be solution providers, meaning they offer products and services as well as solutions. Many research initiatives around the world have focused on product-service integration for numerous years. From an engineering, economic, or social standpoint, many terminologies with essentially identical meanings have been introduced into the PSS landscape.

Concepts like “Service Engineering” [Tomiyama 2001; Lindahl et al. 2005], “Integrated Product Service Engineering” [Lingegård et al. 2012; Pezzotta et al. 2015], “Functional Sales,” “Functional Product Development” [Sarin & O'Connor 2009], or “Industrial Product-Service Systems” [Tomiyama 2001; Lindahl et al. 2005] are close to PSS. PSS has also been closely tied to sustainable development or eco-design [McAloone & Andreasen 2004].

These notions are within the scope of this work and are subsumed under the concept of Product-Service Systems because they are so closely related. The concept of product-service systems adds value by providing a comprehensive, holistic view of technical systems that consider actors, technical artifacts, services, business models, and drives such as sustainability and dematerialization. Constraining is the premise of giving added value to suit customer wants as well as ecological, economic, and social requirements throughout a product-service system's life cycle. Customers' requirements are not simply reduced to a single desire to buy a product.

The primary notion is to sell a defined result, such as the availability or capability of a system to provide value rather than individual products and services. Finally, product and service integration can help preserve or improve a product's or service's functionality, as well as add new products that might otherwise be unavailable. Long-term commitments from the stakeholder network are required for this method to be successful. Specific business models [Tukker 2004] are deployed to achieve this goal, which binds clients to their providers for long periods. A PSS business model may include maintenance, system adaptation to changing needs and boundary circumstances, reconfiguration, or upgrading. That necessitates the partial substitution of services for products and vice versa.

The risk, obligations, and costs of an integrated delivery and operation of product and service shares are split among the stakeholders according to the contract [Otte et al.2008]. During the integrated delivery process, value co-creation among stakeholders is a key goal. To facilitate the distribution of products and services as well as the interchange of information, additional systems and tools must be considered.

The PSS key parts are depicted in a simplified, minimum architecture in Figure 4.8 and its main subcategories in Figure 4.9.

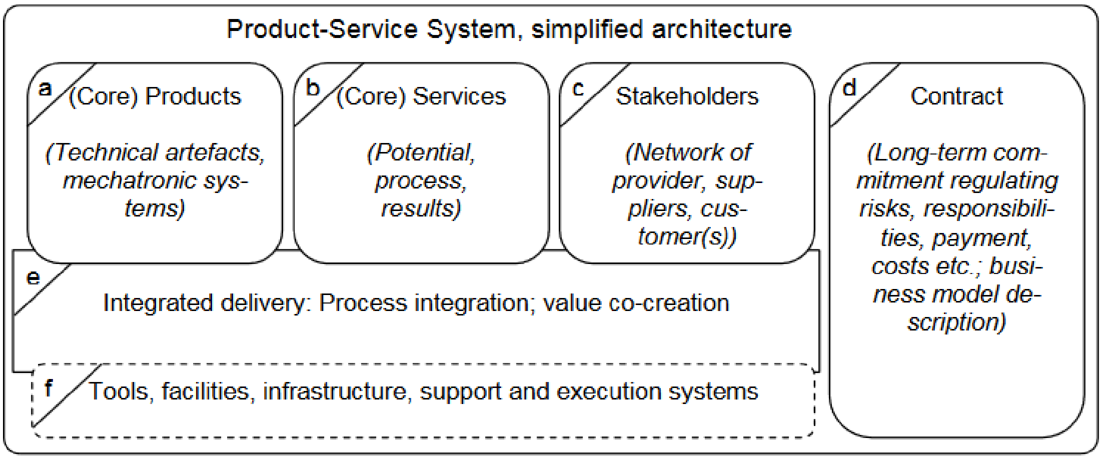

Figure 4.8. Core elements of a product-service system [Mûller & Stark 2008].

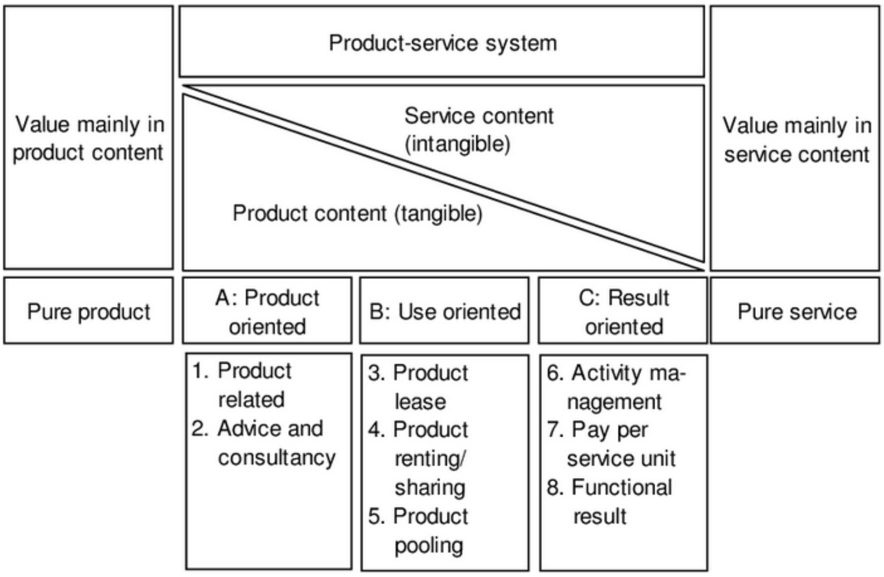

Figure 4.9. Main subcategories of product-service systems [Tukker 2004].

PSS can be considered in a larger sense as a model to describe a defined operating system made up of interdependent product pieces (e.g., machines, stands, conveyor belts) and service parts (i.e., human-intensive activity). Services (e.g., washing services) replace products in result-oriented PSS [Sundin et al. 2009]. Two types of service content can be separated in this case: core services and support services [Yang et al. 2010]. Core services (such as cleaning sheets) are focused on the consumer, whereas support services are focused on the product (e.g., maintenance of the washing machines).

This approach provides research avenues for sustainable development by aligning the product and service parts. Both parts can contribute to the fulfillment of consumers' demands, but there is no theory to back up the assignment of functions to the product part, the service part, or a hybrid of the two.

3.3 Goal-Function-Behavior-Structure (GFBS)

GFBS is a method based on FBS [Gero 2004] and addressed on the research works of [Mauger 2014; Sadeghi et al. 2016, 2017] that models the design objective as a Product-Service System that relies on the features or uses to be offered to customers instead of marketing goods. This model integrates the use of goal, a concept that is not commonly used in mechanical engineering but provides an interesting proposition from a product-driven design perspective.

As defined by Gero and Kannengiesser, requirements are the input to the design process [Gero & Kannengiesser 2004]. The notion of Requirement is developed from the concept of Goal, following the concepts of Goal-Oriented Requirements Engineering [Van Lamsweerde 2009]. A requirement is a goal that has been reduced to a statement about what the system will perform (i.e., the objective has been operationalized) [Letier & Van Lamsweerde 2002]. The origin, or driving force, of the requirements definition is thus understood as the goal. It gives the necessary rationales for the designer to comprehend the Requirement and aids the decision-making process during designer-customer interactions. By including intermediary constructions in the definition domain, the shift from goal to requirements is structured. The product model of GFBS provides the following definitions:

- Goal: objective or requirement established by the consumer that the system will fulfill by cooperating with its components (i.e., subsystems) and creating its mission.
- Function: refinement of the goal transformed into an action of the system to operate on its surroundings, conceived without a context, to cause an external occurrence that leads to a higher Goal achievement.
- Behavior: context-dependent (e.g., time, space, pre-conditions) characteristic of the system (or sub-function) correlated with or derived from its configuration (i.e., its components).
- Structure: The system's physical and intangible elements and their interactions explain how it has been built.

The GFBS and PSS modeling constructs are combined in a requirements specification model based on the defined ontology. PSS constructs the object of research, whereas GFBS structures the process. At a macro level, the Goal and Function constructions are linked to the global system (i.e., PSS). Behavior is initially linked to the overall system (Sys) and then to its Product and Service parts (Pro and Service) (Ser). Throughout keep things simple, the Structure notion is applied to the entire system. This section's GFBS design theory is organized into six steps (Figure 4.10), and it focuses on the system's design (not its components). These steps do not repeat themselves. In order to use the back and forward loops, they must be introduced during the briefing process. The zigzagging principle of Axiomatic Design [Suh 1990] should be remembered. This theory can be used to deduce a number of design procedures.

Design is used to find a solution to a problem. The context of the system represents the current challenge. Unsatisfactory data about environmental aspects describe this context (i.e., external elements). As a result, goals indicate the desired state of affairs or conditions that the system should accomplish during its development. The design process' input is the system's goals (GSys), which are created and refined in collaboration with the client. The framework's decisions are guided by the goals.

1. Function generation: functions are actionable skills that help achieve one or more goals, either alone or in combination with other functions. During this step, the designer transforms states of affairs or environmental circumstances to accomplish or sustain into system abilities to act, irrespective of technical solutions.

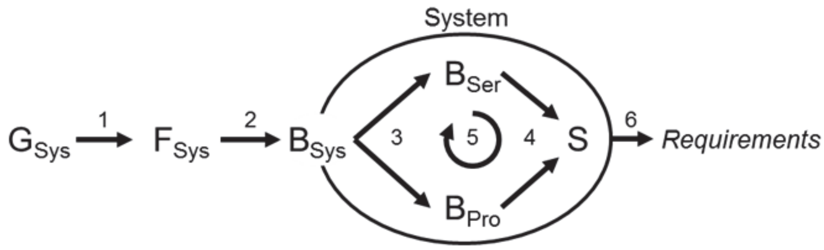

Figure 4.10. GFBS conceptual model for PSS.

2. Function allocation: the designer sketches how the system would act to supply the required functions at this stage. As a result, a description of core solution concepts is produced, but no information regarding the components is provided (i.e., behavioral description of the system rather than structural description).

3. Behavioral refinement: the designer refines how the system will perform functions in terms of product attributes (i.e., properties) (BPro) or service attributes (i.e., activities) (Ser) based on the core solution concepts (BSer). Product attributes (BPro) describe the expected behavior of the system's product portion under particular conditions (i.e., passive behavior), whereas service attributes (BSer) describe the expected behavior of the system's service part (i.e., active behavior). The defined system's goals drive the decision to refine a system's behavior (BSys) to either an active (BSer) or a passive (BPro) behavior of its components (GSys).

4. Structure Synthesis: expected behaviors are linked to basic or combination of system components that are more or less independent of one another. A nomenclature or a product breakdown structure lists all of the system's needed components (i.e., structural description of the system).

5. Requirements processing or Behavior-Structure balance: at this stage, the dependencies between behavior and structure pieces are verified for compatibility with the clients' requirements (e.g., a limited number of structural elements can only ensure a limited number of behaviors). To adjust, lessen, or abolish requirements on the system in accordance with the established goals, a balance is struck between them (Mauger & Kubicki 2013).

6. Requirements specification: this process entails synthesizing the system's (globally) and its components' (locally) requirements, as well as their characteristics. It matches the system's design description as stated in Gero's model (Gero 1990).

3.4 GFBS and BES comparison

The theoretical modeling phases and function models in systematic design theories and methods are intended to lead designers to a possible solution definition concept in their reasoning. Such modeling phases and function models mean switching between function modeling viewpoints discussed in these models [Eisenbart 2017]. Functions are related to the goal or purpose a system is designed. The proposed approach's system modeling is based on FBS's concepts [Gero 1990] regarding the interactions between the external, interpreted, and the expected world. These concepts are directly related to the product's characteristics through its functions, behavior, and structural properties. However, to integrate these elements into the proposed method and use them as information sources and decision-making tools, it is necessary to consider the three different approaches exposed in the previous sections.

Compared to GFBS, the proposed approach defines the product modeling as a set of systems representing different steps of the product characteristics distinguishing the four main concepts of Goal-Function-Behavior-Structure (Figure 4.11).

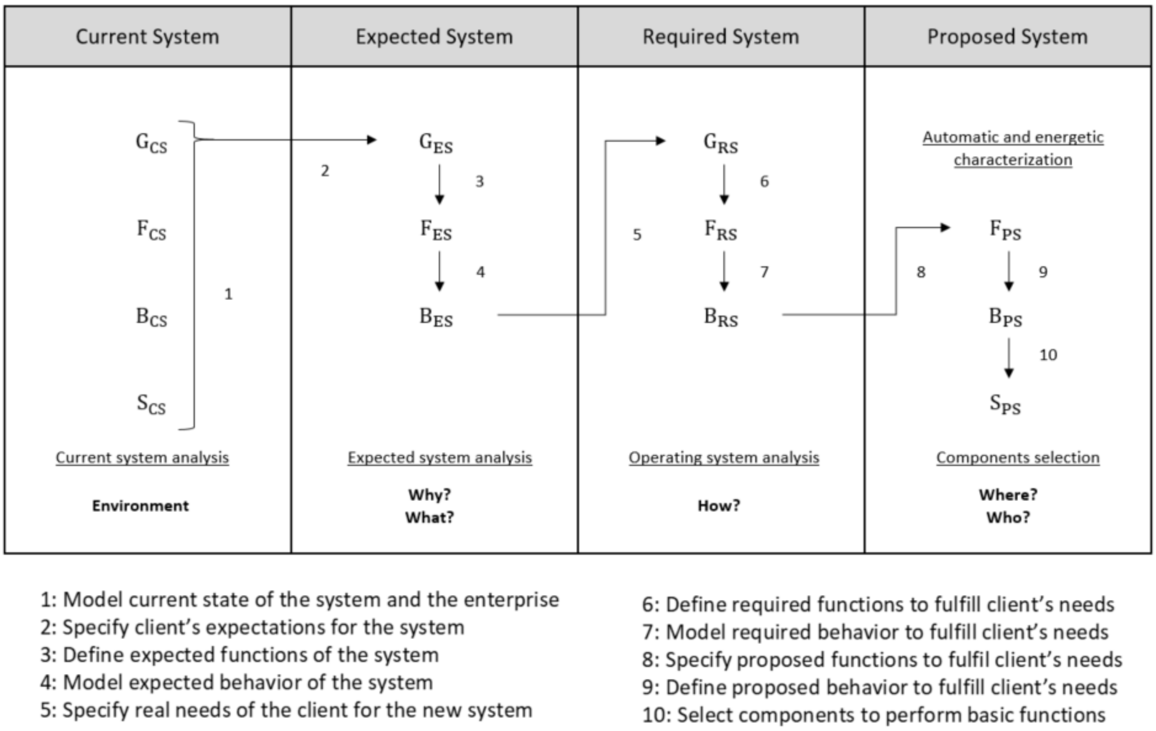

Figure 4.11. Comparison between GFBS and BES.

The goal defined in GFBS provides the means to express main and complementary objectives for the basic design activities. These objectives shape the needs in terms of time, cost, and performance to model the system employing the study objects. Nevertheless, the proposed method needs to provide enough information for decision-making based on predefined criteria related to the expertise to be used for the system. Human factors and safety assessment define those criteria in this study, leading to energy flow characterization to model the system's behavior. The concept of energy modeling is introduced and explained in the following section.

4. Behavior-Energy-Structure (BES) proposed system model

During the early design phases, specific information is needed to evaluate particular parameters defined by the customer and the client. Those parameters change depending on the design project's goal, and it is essential to be able to identify the required information as part of the design process. For example, one goal is to provide a suitable integration of human safety in the early design phases for this study. In the literature review, some studies have used energy flow for the safety assessment of production systems [De Galvez et al. 2017]. Energy is a generic and common element to functional and organic architecture. It is, therefore, a privileged vector of passage from one architecture to another. It, therefore, facilitates design.

Moreover, it also represents an important element in the analysis of safety, as seen in the literature review. That will therefore make the collection of data for the health and safety analysis easier. The use of energy provides enough information to define the system's organic architecture and a solid base to perform safety evaluations. The application of BES is made through Energetic Technical Functions that appear in the second phase of the method using the gathered information during Task Clarification.

However, this approach is represented along all the modeling activities using a combination of the three concepts discussed in the literature review. The logic sequence allows to fully define a system model based on its functions, behavior, and structure.

Based on the modifications needed in the current system analysis and identified in the expected system analysis, the Operating System is modeled from Basic Functions that determine the system's possible new components. So, the general model of the Operating System needs to be completed by selecting technical solutions. These solutions are chosen based on the different manipulations of energy flow that exist inside the system. Two key elements intervene during the phase, Automatic Technical Functions (ATF) and Energetic Technical Functions (ETF). These elements ease the transition from Basic Functions to system components by regrouping functions that execute the same actions. It is important to note that the energetic approach allows the implementation of other types of analysis different from the safety one using the same parameters. Figure 4.12 shows the evolution of the product model for the set of systems proposed for GFBS. For the first three systems (current, expected, and required), the approach is mainly based on Behavior-Structure, due to the nature of the information available. Then for the proposed system, the model includes the energetic approach, first through the ATFs and ETFs' behavior, and then through the components' structure to finally complete the conceptual model.

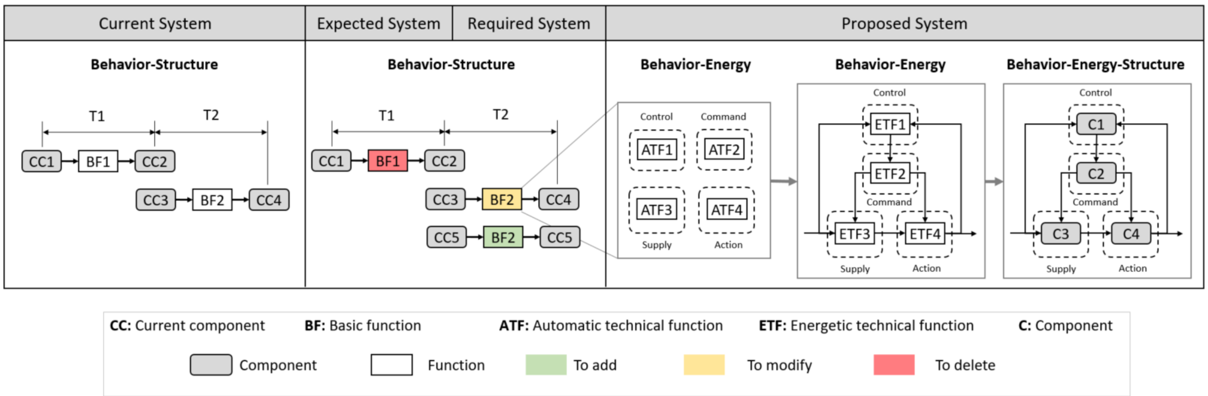

Figure 4.12. Development of the Behavior-Energy-Structure model.

The introduction of ETF to the product modeling allows the designer to have a clear perspective of all the energy manipulations that the system executes and how they add to the overall production process. Based on this, it is possible to characterize the technical solutions needed to ensure each Basic Function. In conclusion, these concepts allow to complete the product model with three levels of decomposition, interactions (Basic Functions), type of action (Automatic Technical Functions), and energy distribution (Energetic Technical Functions). Identifying these elements is closely linked to the study objects proposed in the method, explained in the following chapter.

The BES paradigm does not introduce any changes to the Goal and Function constructs. A goal is a state of affairs or condition established by the clients that the system (i.e., planned facility) must meet through the cooperation of its components (i.e., sub-systems) and determines the system's raison d'être (i.e., answer to the question "Why is it needed?"). A function is a capability offered by a facility to its customers that allows them to transform their environment from state A to state B, maintain or avoid state C, or maximize state D.

The terms function and goal refer to the concept of a black box system (i.e., the external part of it). The majority of them are concerned about the environment. Their combination gives insight into how things should be done in order to meet the needs of clients. They place restrictions on the final result rather than the method or means of achieving it.

4.1 Behavior

In this study, the notion of behavior is used to structure the numerous elements from design phases and steps discussed in Chapter 3, as well as to introduce a new complimentary construct. It is necessary to distinguish between the behavior related to functional architecture and that related to organic architecture. The first is represented by the characteristics of the mission, the Basic Functions, and the Automatic Technical Functions. The second is represented by the characteristics of the Energetic Technical Functions and the Components.

The FBS definition of Behavior includes the concept of an attribute derivable from Structure. As a result, two types of behaviors are distinguished: behaviors of the components related to interactions (i.e., Activity) and energetic behaviors (i.e., Treatment) (i.e., attributes derivable from the Structure). Components behaviors are referred to as "properties" in the Characteristics-Properties Modeling (CPM) methodology [Weber 2005]. According to Weber's definition, Properties cannot be influenced directly by the designer [Weber 2005]. They're called "external attributes" by [Hubka & Eder 2008], however they're called "functional requirements" in Axiomatic Design [Suh 1998]. Activities are active, whereas properties are passive.

Gero utilizes a window as an example to teach the concept of behavior [Gero 1990]. According to Weber's definition, a window's light transmission or ventilation rates are considered product behaviors or quality of the window. Based on what a window is, such behaviors are normal. In this study, opening or shutting the window is considered a change of the functional case, and it refers to a modification of the local context and, by consequence, the system's behavior.

A Behavior is defined as an activity (action or reaction) or a property of a system (or subsystem) in response to specific circumstances or triggering events and is associated with or derived from its Structure (i.e., its components), answering the question "How and When does/can the system perform a Function?". Figure 4.13 shows the automatic characterization model, an example of the behavioral aspect of the proposed approach. The different Basic Functions and their interactions determine the behavior of the future components that will execute them.

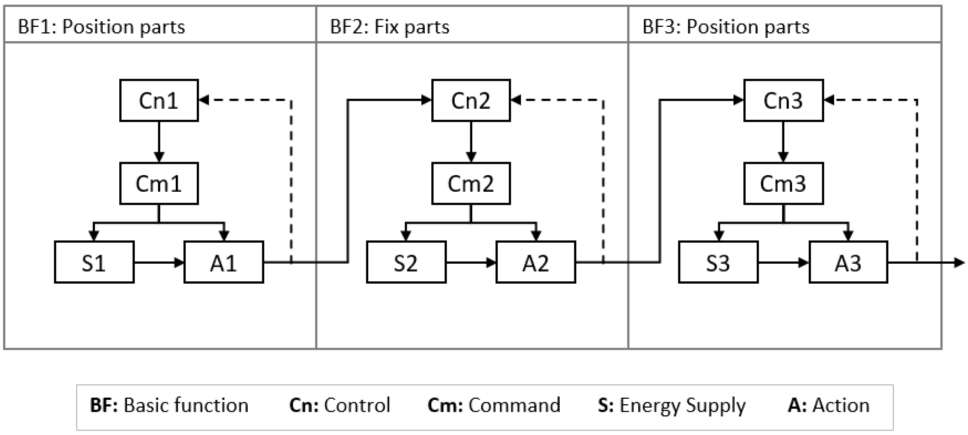

Figure. 4.13. Automatic characterization model.

4.2 Energy

In this study, the idea of energy is used to describe all the sources and flows of energy related to the system (internal and external). This energetic characterization allows describing the internal behavior of the system through energetic functions. Energy comes in a variety of shapes and sizes. Its natural form, or the form imposed on it, provides information about its potential applications. Energy systematically links the behavior and the physical elements. In other words, between the functional and the organic. This characteristic fundamentally makes it possible to guide the passage from one to the other (which the "FBS" model does not make it possible to do, for example). Furthermore, incidentally, energy also provides the required information for safety analysis during design.

A given function is systematically realized through the coordinated combination of different energy flows physically carried by components. This fact justifies the systematic link between functional and organic. Time must be presented as a fundamental quantity when a flow is involved. The physical event in question can only be comprehended by the interplay of energy, matter, and information referred to time. In this study, the energy flows considered inside the production system are determined by their nature, form, and application point. The nature is defined by the type of energy:

- Kinetic
- Hydraulic
- Pneumatic
- Thermal
- Electrical
- Chemical
- Electromagnetic
- Nuclear
- Electrostatic
- Elastic
- Gravitational

The form is defined by the characteristics of the energy flow. For example, the output energy flow of an electric motor is considered rotational kinetic. On the other hand, the output of a linear actuator is considered linear kinetic. The point of application is defined by the interactions of those energy flows with the different components of the system. That information is used mainly for the Detail Design phase of the system, but it is also useful for the safety analysis explained in Chapter 5. It is also possible to apply the quantification of the energy flows based on the functional modeling of [Malmiry et al. 2016]. That modification makes use of an energetic system model that is based on CPM [Weber et al. 2003; Weber 2005, 2009] and CTOC [Pailhès et al. 2007, 2011]

The previous terminology is frequently tied to real physical or technical representations in the technical sphere. The manifest nature of energy is frequently used to define it. That is referring to mechanical, electrical, or optical energy, for example. There are numerous ways to convert energy. For example, electrical energy is converted into mechanical and thermal energy by an electric motor, or chemical energy is converted into mechanical and thermal energy by a combustion engine (Figure 4.14, the use of the energy conversion matrix is explained in Chapter 5). Depending on the context, the problem, or the type of solution, one type of conversion (of energy, material, or communications) may win over the others in technical processes.

Input \ Output	Kinetic	Hydraulic	Pneumatic
Kinetic	Mechanisms	Hydraulic pumps	Pneumatic pumps
Hydraulic	Hydraulic actuator	Valves	
Pneumatic	Pneumatic actuator		Valves

Figure 4.14. Energy conversion matrix (extract from Appendix 2).

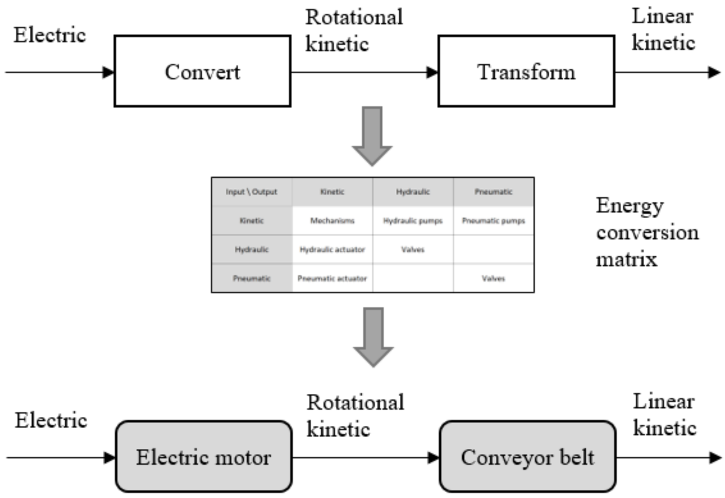

Figure 4.15. Energy flows and components selection.

Each Automatic Technical Function has an energy chain whose sole purpose is to transform a supply energy flow into the required energy flow to perform a given function of the Operating System (Figure 4.15). This energy chain comprises links representing the physical components of energy transformation necessary to meet this goal. For example, in the case shown in Figure 4.15, the conversion from electric to linear kinetic is made in two levels: first a conversion and then a transformation, but it is also possible to direct conversion. It is important to specify that there are several possible energy chains for a given function: the one selected is completely compatible with the technical constraints that apply to the function. The criteria to choose an energetic chain over another depends on the technical constraints defined in Task Clarification. Other criteria can be added, such as the cost and time of supply of the components, their reliability, or their simplicity of maintenance.

For example, if the input energy flow is electrical energy and the required output energy flow is rotational kinetic energy, energy conversion can be made through different energy chains: electric-rotational kinetic; electric-linear kinetic-rotational kinetic; electric-hydraulic-rotational kinetic (Figure 4.16). The choice of which solution is the most appropriate for the design problem is determined by the context and constraints of the system (this aspect is explained in more detail in Chapter 5).

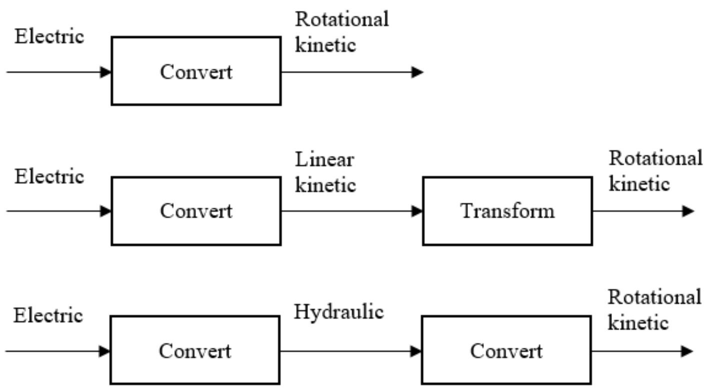

Figure 4.16. Example of energetic chains.

4.3 Structure

In this study, the idea of Structure is utilized to collect together all of the constructs that characterize a system's components and their arrangement. It refers to the components, which are static. The structure is described by the components' characteristic attributes, which are those that may be directly controlled or decided by the designer (e.g., material, shape, proportions) [Weber 2005]. In some design theories, they are referred to as internal qualities [Eder 2008] or design parameters [Suh 1998].

Structure refers to the system's physical and nonphysical components (e.g., software), their description (i.e., geometry, topology, and materials), and their relationships describing what they are made. It is also necessary to specify here that these relations are functional relations and physical interfaces between components. Note that the latter corresponds directly to the nomenclature of the system (bill of materials). More broadly answering the question "Who (i.e., which resource) has to act in the system to perform a Function when needed, and where is it performed?". Figure 4.15 shows the representation of the structural components in different diagrams of the proposed approach, (a) represents the model of the current system in the case of an existing production system, (b) represent the changes needed to be made to the current system to achieve the expected system results and (c) represents the choice of components for the operating system.

The energy-based modeling approach aims to represent the behavior of the production system and simplify the use of decision-making and analysis tools to evaluate other aspects related to the client's needs and design project requirements

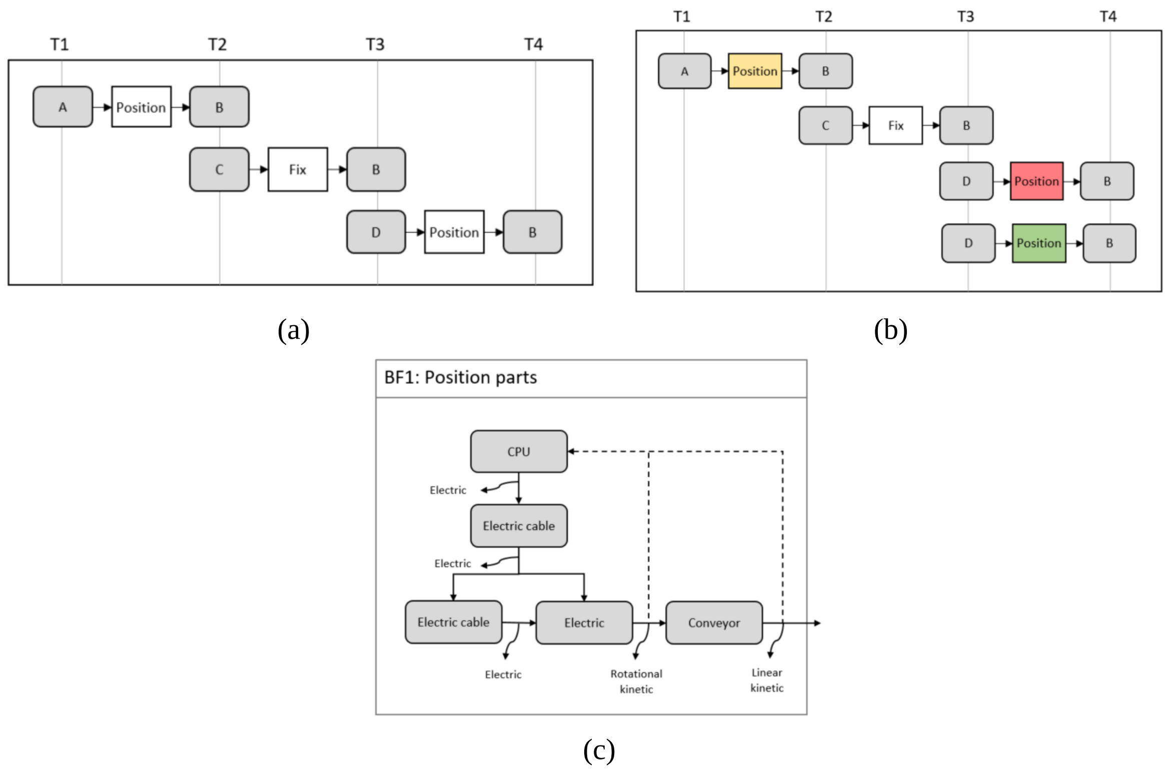

Figure 4.17. Structural modeling.

5. Discussion and conclusion

The energetic modeling approach presented in this chapter completes the proposed method by providing the tools to represent the behavior, energy, and structure of the Operating System. The representation of the behavior is directly related to the functional architecture of the system, and the structural representation is directly related to its organic architecture. The passage between those two architectures is made through the energetic characterization, which on the one hand, completes the functional architecture and, on the other hand, provides the needed information to choose the Operating System components.

The dynamic between functional and organic architecture is always a critical point on every design project because the current design approaches do not address that passage in-depth, and most of the time is up to the experience and knowledge of the design team to make that transition. The proposed approach provides a solution for that recurrent dilemma, which becomes one of the contributions of the method.

The system model is crucial for the design process because it reflects all the changes and decisions made during the different steps and phases to achieve the expected result. In that sense, the system model greatly influences the design process because it provides a set of intermediate goals to achieve. The identification of other system model approaches defined in the literature allowed identifying the right set of goals to use in the proposed method. The energy-based approach was the result of that analysis.

Moreover, the energetic characterization serves at the same time as a tool to define and complete the system and as a source of information required to perform different types of analysis using the same information obtained for the design process. As discussed in this study, the focus is human safety during the design of production systems, and the energetic modeling perfectly allows the use of safety assessment methods and tools during the design process. In this chapter, that integration has been discussed briefly, but in Chapter 5, a more in-depth analysis is addressed.

In the following chapter, the proposed design method is fully defined based on all the elements that have been discussed. A case study is used to describe and validate the application of the method, and the elements needed for safety integration are discussed.

Chapter 5: Proposed design method, safety integration, and illustration on a case study

Abstract

This chapter presents the proposed design method in a more sequential manner, combining all the elements defined in the previous chapters and showing its application using a case study of a welding workstation. The case study is part of a field experimentation made in a factory of the region where the proposed method was put to practice. There is an introduction to the case study where its main elements and characteristics are explained. Then, the chapter continues following the first two phases of the proposed design method and how they are applied to the case study. Every phase is explained in more detail based on the design steps and activities. As said in Chapter 3, the steps are different on every phase, but the design reasoning activities are applied iteratively, so the same set of activities is found for every step. Then the application of safety is explained, linking the case study and the different risk identification tools and methods applied to the method. Finally, the chapter concludes with a discussion of the design method results in the case study.

1. Introduction

This chapter shows the sequential application of the proposed method on a semiautomatic welding workstation, which is part of an existing production system in a factory of the region. The objective is to explain the application of the design process step by step and all the considerations needed to be taken based on the different elements discussed in the previous chapters and the specific aspects of the case study. It is important to clarify that the design objective is to propose a solution to the client's needs based on the preexisting workstation in this case. That means that the choice of the final solution will be affected by the available resources (current components and parts), but they will not limit it.

The welding workstation (Figure 5.1) is divided into two, the welding and the feeding zone. The feeding zone is where the worker charges the unwelded parts to be fed to the welding zone and also where the finished parts are discharged to be sent to the next station. There are two different racks for the welded and unwelded parts to store the parts before and after the welding process. The operator is in charge of moving the parts from the rack to the rotational table and fixing them to the table using different pins or clamps depending on the part reference. Also, the worker is in charge of unfixing the welded parts from the previous welding cycle and store them in the allocated rack. The robot performs a specific welding trajectory in the welding zone depending on the type of parts attached to the table. The two zones are physically divided by a protective barrier, and a rotary table placed in between the two zones makes the exchanges of parts.

The problem expressed by the client was the time balance between the worker's activities and the automatic welding performed by the robot. In the current system, the worker takes more time to perform the task than the robot, which implies iterative idle times on the welding zone.

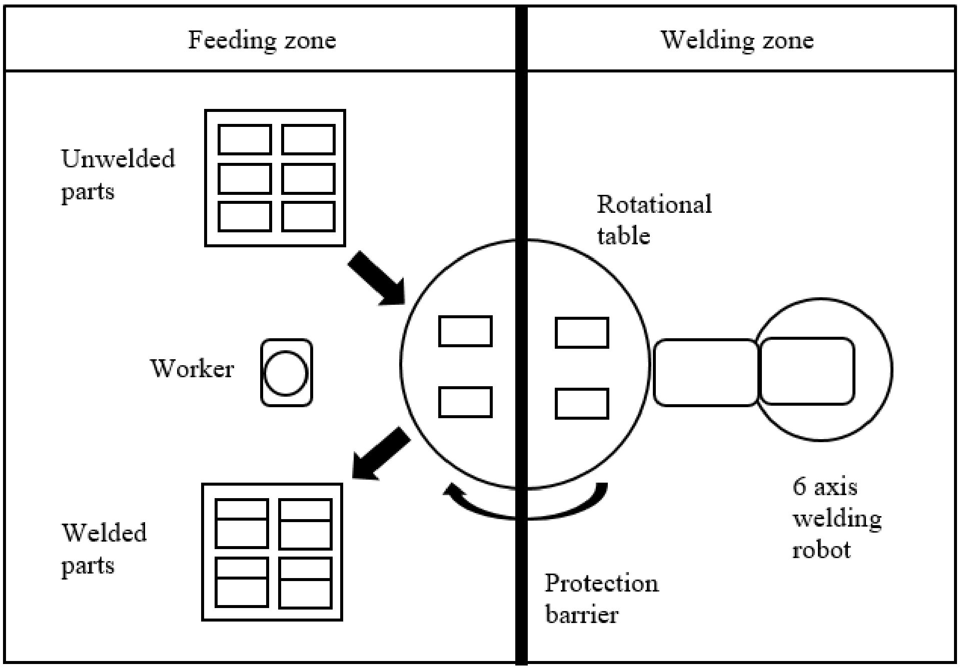

Figure 5.1. Distribution of the welding workstation.

A detailed explanation of each of the two phases, six steps, and five design reasoning activities is described in the following sections. The use of the case study provides clarifications on the way how the method should be applied.

2. Task Clarification for the welding workstation

The first phase of the design process starts with the definition of the design task. In this case, the objective is to determine the perimeter of the study for the welding workstation, model its current characteristics to use as the starting point for the operating system's design, and provide the technical requirements needed for the final solution.

This section describes the application of the three steps that compose Task Clarification and illustrate the use of the five design reasoning activities that appear iteratively on every step. For the first step (Current System Analysis), only three design reasoning activities are considered due to the nature of the step: specify, model, and validate. The first step does not require the activities of Design or Evaluate and Optimize because it is meant to show the current state of the production system or, in this case, the workstation. In the case of the design of a new production system for which no prior information is available to consider as a starting point, it is possible to start the design process by the definition of the expected system. For the other two steps of this phase, all the design reasoning activities are considered.

2.1 Current System Analysis (CSA)

Given that a welding workstation already exists in the factory, its main functions, interactions and constraints need to be modeled to assess customer's needs in an exploitable form for the design team. This modeling is crucial because it will settle the basis for the models of the other two systems (expected and operating). The level of detail and complexity of the model is determined as part of the perimeter of the design problem because all data collected must be used in the subsequent phases, that is why the scope and level of detail of the study and, therefore, of the modeling must be adapted to the problem posed by the client. For example, if the model is complex and has a very high level of detail, but only a small part of the system needs to be modified, the amount of relevant information would be small, implying a loss of time and resources for the system design team. The main purpose of this stage is to represent the current system as an exploitable model following the three successive design reasoning activities.

2.1.1 CSA Specify

In order to identify the actual client's needs, it is important to specify the industrial operations of the costumer in question clearly. The components that enable this activity to be carried out and its interactions must also be identified, as explained in chapter 3. Every industrial company comprises five complementary systems with a certain granularity level (see Chapter 3, section 2.1.2). In the case study, the granularity level is determined by the nature of the design problem (table 5.1). Since in the example, the object of study is not a complete factory or a production system, the level of granularity is Technical System, so the model of the Current System is only going to be composed of technical components. The need of the customer is to reduce the feeding time for the robot. The worker executes this operation, and it takes approximately twice the welding time. Those interactions determine the system's current behavior and are the output information of this first activity to develop the model of the current system.

Table 5.1. Components interactions in the welding workstation.

Entity A	Interaction	Interaction scope	Entity B
Storage rack	Support	Part reference	Unwelded parts
Worker	Position	In reference to the table	Unwelded parts
Table	Support	Part reference	Unwelded parts
Worker	Fix	Geometrical tolerances	Unwelded parts
Table	Position	In reference to the robot	Unwelded parts
Robot	Weld	Geometrical tolerances	Unwelded parts
Table	Position	In reference to the robot	Unwelded parts
Worker	Unfix	Geometrical tolerances	Unwelded parts
Worker	Position	In reference to the rack	Unwelded parts
Storage rack	Support	Part reference	Unwelded parts

2.1.2 CSA Model

Based on the collected information in the previous activity, the aim is to represent components, interactions, and technical constraints in an organized manner. In Figure 5.2, there is an example of the graphical formalism used to represent these elements. Each interaction is set at a time that allows defining the sequencing of the interactions along with the components that are interacting at that time. Indeed, several simultaneous interactions can happen simultaneously with different execution times for each of them. The execution time of each interaction is formalized through a property. The components or interactions properties are represented as small folders on the right corner. There could be specific constraints related only to components, only to interactions, or both. The criteria to evaluate these components and interactions are defined by the type of parameter, target value, tolerance, and control mean based on the notion of requirement defined by System Engineering. Table 5.2 shows the detail of worker's characteristics.

The model of the welding workstation model is shown in Figure 5.3. The model represents the main elements that take part in the welding process as well as their interactions through a complete cycle. Time intervals allow representing anteriority constraints for the functions carried out. The fact that a component or interaction is imposed by the client results in a specific property. This model needs to be validated in the following activity.

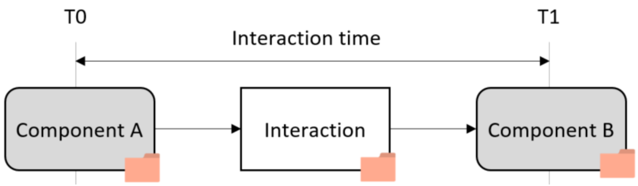

Figure 5.2. Example of diagram to represent components and interactions.

Table 5.2. Characteristics of a component.

Component	Type of parameter	Unit	Target value	Tolerance	Mean of measure
Worker	Height	m	[1,6 ; 1,90]	± 0,1	Meter
	Weight	kg	[60 ; 130]	± 20	Balance
	Maximal charge	kg	10	± 5	Test
	Visual acuity	-	20/20	-	Test

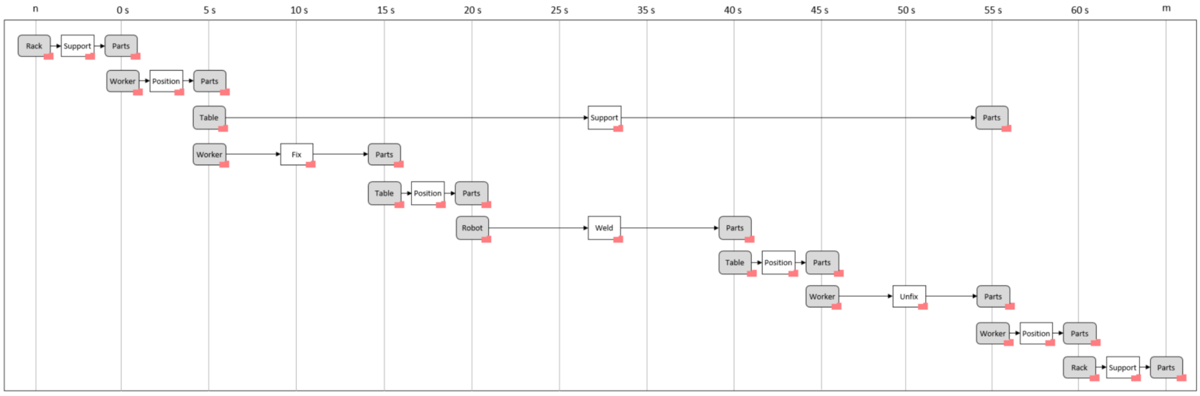

Figure 5.3. Current System Modeling of the welding workstation.

2.1.3 CSA Validate

To validate the Current System model, it is necessary to examine the accuracy of the treated elements (constraints, components, and interactions) concerning the studied activity. Then, make sure that the customer's requirements are taken into account in the model's core functions. Following this reasoning, it becomes required to assess the model's and the real system's structural adequacy from both a static and dynamic perspective. The cause-and-effect relationship between consumer expectations and the description of Basic Functionalities becomes a critical component of the stage's validation.

Based on physical verification, the model's function, interactions, and components in the proposed model correspond to those in the real system. Therefore, the model can be said to behave similarly to the Current System. This similarity allows the representation to be validated and progressed to the next stage.

To sum up this section, CSA is the diagnostic of the current status of the system, from which all further alterations and improvements will be derived. Special attention must be paid to the amount of detail in this modeling to avoid wasting time and resources. The properties of the Expected System are discussed in the following chapter using the Current System model.

2.2 Expected System Analysis (ESA)

The Expected System represents all the functions that the customer expects of the production system, so in this step, the design team can define what the customer actually needs considering the current system model. The aim is, therefore, to define a system that can meet the requirements of the company. In the case study, the objective is to have a system where the operation time of all the worker tasks takes less than the operation time of the welding process, but this objective needs to be expressed in an exploitable way for the design team.

2.2.1 ESA Specify

This first activity has for objective to specify the perimeter of the expected system. The design team has to use all the information defined during CSA and ask the client to express their needs regarding cost/time/performance/constraint. The detail of the functions is the designer's responsibility and is the subject of the next step. That information is used to determine the main differences between the current system and the expected system. In the case study, the current system model and the characteristic of the components and interactions are already defined, and the client expressed that an ideal system will allow reducing the time of the worker's operation to half the time of the welding process either by automating some parts of the workstation or by changing the order of operations. That information provides the input data for the following activity of design.

2.2.2 ESA Design

This phase aims to identify the components, functions, and interactions to be removed or changed and identify those to be generated to fulfill the requirements. It must be done with the data collected at each level in the previous step. That requires identifying components and interactions that do not meet the customer's needs in their current state. Components and interactions are maintained if these features can evolve easily to satisfy customer requirements (e.g., software update, different settings). When these elements cannot evolve enough, they are replaced by new ones that suit the requirements. In general, it should be noted that there may be several solutions to meet the customer's needs.

For the study case, the list of components interactions needs to be analyzed to determine which to keep, change, modify or delete, considering the time requirement expressed by the client of reducing the duration of the worker's tasks. The activities that consume more time are those related to the fixation of the parts to the table and their discharge after welding. So, the elements to be modified are the table and the fixation/detachment of the parts.

2.2.3 ESA Model

This activity aims to formalize and organize the functions and interactions directly related to the customer's needs. The identification of changes made in the previous activity is used to shape the representation of the Operating System. The changes in the type of parameter, target value, tolerance, control means are needed to be expressed as requirements for every one of them. So in this step, it is necessary to define the properties of the expected system to be used as the reference for the following design steps.

As seen in Chapter 3, every element directly linked by the customer need is clearly distinguished by a color code in which green is a new element to be added, yellow is an item to be modified, and red is an element to be deleted. This code helps distinguish the entities and interactions to delete, modify, or create from the unchanged elements. Figure 5.4 shows the model of the Expected System with the respective color code. In this case, only modifications are needed.

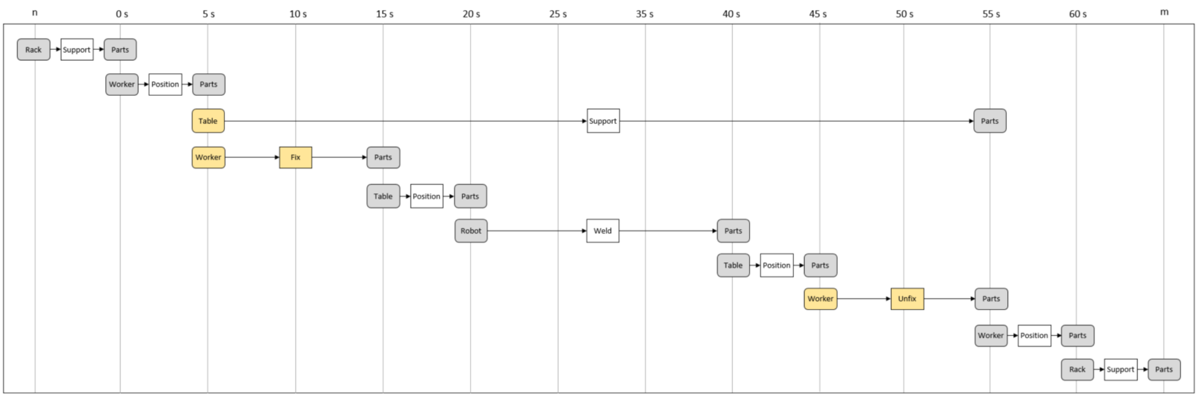

Figure 5.4. Expected System Modeling of the welding workstation.

2.2.4 *ESA Evaluate and Optimize*

This activity ensures that the possible solutions are relevant by comparing the customer's needs with the current and expected system. That is to consider criteria that will determine the most fitting solutions for the design problem. For the case study, since the principal parameter expressed by the client was related to time, the modifications needed to be made in the Current System are located in the components and interactions already defined in the model that consumes the most time.

2.2.5 *ESA Validate*

This activity aims to verify the relevance of a modelling system by comparing the modelling of the system and the objectives of the system and validating the results of the phase.

Due to the nature of the modifications needed to the Expected System model of the welding workstation (only modifications with no new components or interactions), they correspond to the expected results and respect the requirements (modification of components that are not subject to any constraint expressed by the client), so it is possible to continue to the next stage.

In conclusion, for this section, the differences between the Current System and the Expected System determine how far the final solution can go concerning its current state. One of the assets of the method is the fact that it uses the same documents with the same formalism at all the design steps and modifying and enriching it, which simplifies the modeling task for the design team. The complexity of the document is well proportional to that of the system.

2.3 Operating System Analysis (OSA)

The model of the Operating System is formed by new or modified components and interactions that satisfy customers' requirements. It is necessary to specify here that the interactions are not Basic Functions but Automatic Technical Functions of Action. This description occurs in three moments, first in the mission of the Operating System and its life cycle are specified. Then, the environmental stakeholders and Basic Functions are identified. Finally, connections between technical constraints related to stakeholders and Basic Functions are established to determine to what extent they affect each other (Figure 5.5).

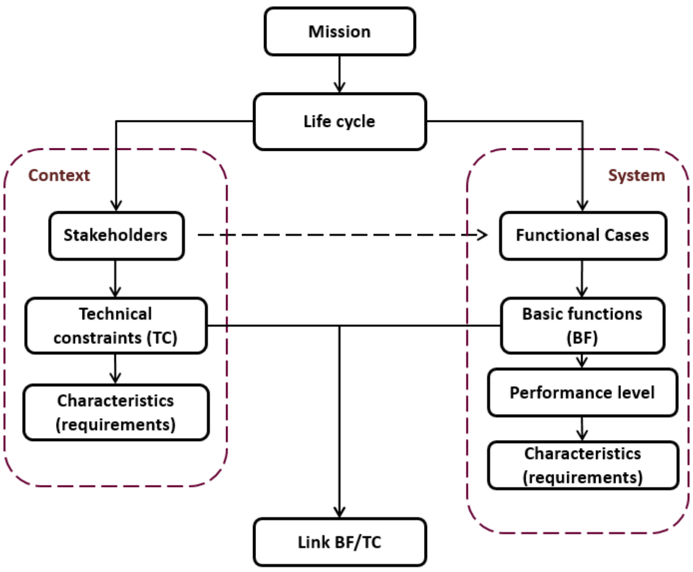

Figure 5.5. Diagram of the Operating System elements.

2.3.1 OSA Specify

During this activity, the operating system's mission, life cycle phases, and technical constraints are defined. The mission can be defined as a change of state of an Operated stakeholder. In that definition, the state is a characteristic of behavior, energy, or structure (cf. BES model). The mission has to be defined based on the expected result of the design process and the modifications needed to be performed in the Current System. The Operating System life cycle must also be defined and related to the needs of the customer. It should be noted here that the life cycle of the Operating System is defined from the mission of the operation phase. It should also be specified that the other phases of the life cycle correspond to a particular environment (or context) in the life of the Operating System. The list and the choice of the phases constituting this life cycle are defined with the customer.

The standardization of the way the mission is expressed is one of the key features of the step to formalize the Operating System. That can be accomplished by writing the mission in the form of an infinite verb and two complements that refer to time, cost, and performance requirements.

In the welding workstation example, and based on the elements to be modified, the design goal is to reduce the time of fixation and discharge of the parts. It is necessary to design fixation means that take less time to charge and discharge the parts. So, the mission of the Operating System can be expressed as: "Maintain the parts in the correct position throughout the welding operation." The mission as it is expressed here corresponds to the notion of change of state of an Operated Stakeholder (Operated Stakeholder: parts to be welded; Initial State: free parts (random position and orientation); Final State: parts positioned and maintained (known and fixed position and orientation). Also, the life cycle of the Operating System will only consider the Operation phase.

The identification of stakeholders is made employing a list with all the external elements (physical and nonphysical) that directly interact with the components of the Operating System. The identification of the Stakeholders must be made for each phase of the life cycle of the Operating System since each of them corresponds to a specific context.

2.3.2 OSA Design

The Basic Functions of the operating system that ensure the accomplishment of the mission must be defined during this step, as well as its nature and perimeter. Different functional cases are considered, using the phases of the life cycle as starting point and keeping stakeholders into account. For every functional case, there must be a definition of Basic Functions that take place within that local context. Basic Functions are expressed in the same formalism as the mission, in the form of an infinite verb and a complement that refers to form, position, or sequencing. The list of all Basic Functions required to accomplish the system's mission must be defined by the design team with the help of the client. That list is completed in the following step by defining the levels of performance and properties of every Basic Function. In the welding workstation case, an extract of the list of Basic Functions can be seen in Table 5.4 under the third column.

During the development of the case study, a second team of the Industrial Chair project made a parallel study of the industrial problem by searching for an organizational solution for the change of production from one family of parts to another. That solution was developed independently of the proposed method, but it used the OSA to apply the SMED method (Single-Minute Exchange of Die) [Godina et al. 2018]. The implementation of the proposed model as the starting point of a different method validates its flexibility while integrating different KPIs. The details of the method and the results in the case study can be consulted in Appendix 4.

2.3.3 OSA Model

To formalize technical constraints graphically, a simple heuristic chart is sufficient to detail each interaction between stakeholders and the system as well as their characteristics in the form of requirements. For the study case of the welding workstation, the same process has been applied to identify technical constraints. In Table 5.3, the heuristic chart is shown.

Table 5.3. Heuristic chart of technical constraints for the welding workstation.

Life cycle phases	Stakeholders	Technical constraints	Unit	Target value
Operation	Building	Volume around the workstation	m^3	Non-applicable
	Welding robot	Geometry	mm	1500x700x500
		Position	-	2
		Kinematic capacity	mm	1100x650x300
		Mechanical capacity	axis	6 axis + 1 table axis
	Atmosphere	Temperature	°c	10 to 40
		Humidity	%	50
		Dust	mg/m^3	16
		Luminosity	lux	500
		Noise level	dB	50
		Toxicity	DL50	Low
	Parts	Geometry	mm	See reference
		Position	mm	See reference
		Material	-	Steel S355 and C45
		Surface quality	µm	120
		Weight	kg	10
		Temperature	°c	400
	Welding material	Material	-	FIL ARISTOROD 12.50 Ø1.2
		Temperature	°c	1500
		Geometry	mm	See reference
		Gaseous fumes	mg/m^3	Mison 8

The heuristic chart is also used as a representation method for the Basic Functions. The expected output from every Basic Function must be represented in a manner exploitable by the designer. For the welding workstation example, Basic Functions are also identified using this step. In Table 5.4, an extract of the heuristic chart for Basic Functions and functional cases is shown (the entire table can be found in the Appendix 1). The coefficients A_i are used to determine the target value of time for each Basic Function. Since those values are not fixed, they must respect the following equation, which describes one of the client's requirements expressed in the previous step:

$$\sum_{k=0}^{n} A_i \leq 0,5 * Welding\ time$$

Table 5.4. Heuristic chart of Basic Functions for the welding workstation.

Life cycle phases	Functional cases	Basic Functions	Performance level	Unit	Target value
Operation	Welding	Position the parts to be welded in relation to the system	Operating time	s	A1
			Part reference	-	21
			Degrees of freedom	-	x y z
			Displacement	mm	0
			Weight	kg	See reference
		Fix the parts to be welded to the system	Operating time	s	A2
			Part reference	-	21
			Degrees of freedom	Degrees of freedom	0
			Weight	kg	See reference
		Move the parts to be welded from the storage rack to the holding area	Operating time	s	A3
			Part reference	-	21
			Degrees of freedom	-	x y z
			Displacement	mm	2000
			Weight	s	See reference

The model of the Expected System has to be reused to identify the elements and interactions that need to be created or modified. Using this description, the Expected System configuration can be rearranged to define the configuration of the Operating System. This model will take into account specific technical constraints and Basic Functions to fulfill the mission. In this stage, energy distribution can also be defined within the production system to apply the Behavior-Energy-Structure (BES) model in future phases. That can be achieved using the diagrams and functions of the Operating System.

2.3.4 *OSA Evaluate and Optimize*

This step is necessary to evaluate the compliance of the elements with the system mission. It is important to ensure that future changes are compatible with the current layout by comparing the Current System with the Operating System mission based on possible compatibility issues. The Current System relations with the stakeholders need to be defined to determine the completeness of the technical constraints surrounding operating components. In the example, the Basic Functions proposed are compatible with the Current System because they consist only of modifying some of the already existing components.

Finally, the links between Basic Functions and constraints are defined using the matrix shown in Figure 5.6. This matrix allows the design team to define the technical constraints that affect a specific Basic Function. This information is required in the energetic characterization and component selection steps.

	Technical constraints																				
	Building	Welding robot				Atmosphere						Parts to be welded						Welding material			
Basic functions	Volume around the machine	Geometry	Position	Kinematic capacity	Mechanical capacity	Temperature	Humidity	Dust	Luminosity	Noise level	Toxicity	Geometry	Position	Material	Surface quality	Weight	Temperature	Material	Temperature	Geometry	Gaseous emissions
Position the parts to be welded in relation to the system						×	×	×	×	×	×	×	×	×	×	×	×				
Fix the parts to be welded to the system						×	×	×	×	×	×	×		×	×	×	×				
Move the parts to be welded from the storage rack to the holding area	×					×	×	×	×	×	×					×	×				
Position the parts to be welded on the holding area	×					×	×	×	×	×	×	×	×	×	×	×	×				
Fix the parts to be welded in relation to the holding area	×					×	×	×	×	×	×	×		×	×	×	×				
Free the parts to be welded from the system						×	×	×	×	×	×	×									
Position the holding area in relation to the welding robot		×	×	×	×	×	×	×		×											
Fix the holding area to the base of the welding robot		×	×	×	×	×	×	×		×											
Release the holding area from the base of the welding robot						×	×	×	×	×	×							×	×	×	×
Position the holding area in relation to the storage rack for the welded parts						×	×	×	×	×	×							×	×	×	×
Fix the welded parts to the system						×	×	×	×	×	×	×		×	×	×	×	×	×	×	×
Release the welded parts from the holding area						×	×	×	×	×	×	×						×	×	×	×
Move welded parts from holding area to storage rack	×					×	×	×	×	×	×					×	×	×	×	×	×
Position the welded parts in relation to the storage rack	×					×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Free the welded parts from the system						×	×	×	×	×	×	×									

Figure 5.6. Matrix of links between Basic Functions and technical constraints.

2.3.5 OSA Validate

In this last step, it is important to verify the relevance of subsystems based on customer requirements as well as the relevance of the operating system's technical constraints and Basic Functions. The customer's point of view is always relevant, and that it is crucial that the outcomes of the stage are addressed to the customer to speak about their importance and whether or not the process targets of each stage are met. The Basic Functions proposed for the welding workstation meet the requirement of time defined at the beginning of the project.

To conclude this section, it is important to remember that the Operating System comprises the technical solutions necessary to comply with customer requirements defined in the two previous stages (CSA, ESA). This model is the starting point of conceptual design. That is why the operating system has to be more comprehensive than the two other previous systems. To define technical solutions using OSA is necessary to define two different types of functions explained in the following section.

3. Conceptual Design for the welding workstation

The second phase of the design process aims to choose the working principles and components of the final solution. The Basic Functions identified during the previous phase correspond to a functional need, and it is now necessary to define the associated behavior through two other types of functions. This phase determines the feasibility of the design project based on the possible solutions and their conformity with the customer needs, constraints, and technical requirements. This section describes the application of the three steps that compose Conceptual Design and illustrate the use of the five design reasoning activities that appear iteratively on every step.

3.1 Automatic Characterization (AC)

Automatic Technical Functions (ATF) are groups of Basic Functions that execute activities of the same nature needed to ensure the execution of all Basic Functions. The goal is to identify the complementary ATF for every BF. That definition simplifies the transition from BF to components. This intermediate stage links the functional needs expressed through the BF and the energy interactions from which the organic architecture will be built. It is based on a unique behavioral model that applies to each of the BF and allows the design team to define the degree of autonomy (open-loop, closed-loop, or hybrid operation). This model describes an initial "closed-loop" behavior that can be easily adapted to the desired operation. This model is made up of "Automatic Technical Functions" and "interactions."

3.1.1 AC Specify

This first step aims to determine the complementary functions needed to perform the Basic Functions according to the nature of their activity. During this activity, the goal is to customize the single behavioral model to the nature of the BFs and the connection of the different models to respect the functional cases of the system to be designed.

The application method is to sort the list of Basic Functions and determine if all four types of ATFs are needed for their execution: energy supply, action, command, and control. In the example of the welding work station, all the BF require using the four types of ATF, even if some of them are performed by a single component. The ATF of action always is related to the nature of the BF. That is why the rest of sub-systems formed by the other ATFs are identified in the following activity.

3.1.2 AC Design

During this design activity, the target is to describe the structure of these ATFs through interactions between these sets of functions and the adaptation of the single behavioral model to the level of autonomy required by the BFs considered. This step is based on the fact that any system needs energy supply elements, action components to execute BFs, command devices, and control means. So, from a system point of view, these categories become subsystems of energy supply, action, control, and command necessary to carry on any internal or external function. For the case study, since the BFs consider all the types of ATFs, all the subsystems need to be defined, as shown in Table 5.5.

Table 5.5. Automatic Technical Functions definition

		Energy supply	Control	Command
Action ATF	Position the parts to be welded in relation to the system	X	X	X
	Fix the parts to be welded to the system	X	X	X
	Move the parts to be welded from the storage rack to the holding area	X	X	X
	Position the parts to be welded on the holding area	X	X	X
	Fix the parts to be welded in relation to the holding area	X	X	X
	Release the parts to be welded from the system	X	X	X
	Position the holding area in relation to the welding robot	X	X	X
	Fix the holding area to the base of the welding robot	X	X	X
	Release the holding area from the base of the welding robot	X	X	X
	Position the holding area in relation to the storage rack for the welded parts	X	X	X
	Fix the welded parts to the system	X	X	X
	Release the welded parts from the holding area	X	X	X
	Move welded parts from holding area to storage rack	X	X	X
	Position the welded parts in relation to the storage rack	X	X	X
	Release the welded parts from the system	X	X	X

3.1.3 AC Model

The modeling of ATF is made through a diagram that shows the links and interactions of all the functions. These ATFs can represent a single component or a set of components that execute a specific function for the system. This representation exposes the internal structure of the Operating System graphically even if technical solutions or components have not already been chosen. An extract of the ATF model for the welding workstation is shown in Figure 5.7.

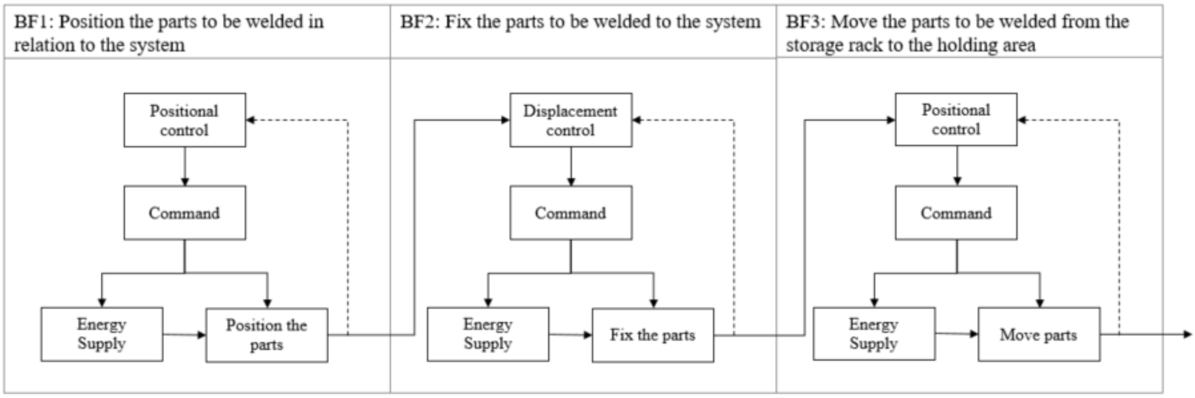

Figure 5.7. ATF model of the welding workstation (extract).

3.1.4 <u>AC Evaluate and Optimize</u>

To evaluate and optimize the completeness of the behavioral model concerning the mission of the operating system is necessary to evaluate time, cost, and performance requirements. The application method is to compare the overall behavior of ATF with the mission of the Operating System, the functional case, and the BF to ensure that the main objective is achieved. If that is not the case, in necessary to identify the aspects that keep the system to meet the requirements and rearrange the general structure of ATF. In the study case, the model meets the requirements defined by the customer.

3.1.5 <u>AC Validate</u>

The last step is to check the relevance of the ATF and the interactions that have been defined and make the decision that will lead to the choice of the solution that will be developed. This decision is made jointly by the designer and the client. To verify this, it is important to apply specific criteria to ensure that the system meets the requirements in terms of time, cost and performance. The interactions defined for the welding workstation are consistent with the mission of the Operating System, allowing to continue to the following stage.

This new layout has been incorporated into the Operating System's general model to make the internal functioning of the system easier to comprehend from a different granularity level. However, it is not clear from this model how to select components or technical solutions that match the requirements; therefore, another set of technical functions must be developed to fully complete the conceptual design, as stated in the next section.

3.2 Energetic Characterization (EC)

Energetic Technical Functions (ETF) are actions that transport, storage, or converts energy inside the Operating System. They are the characterization of ATFs only in terms of energy manipulation and treatment. That is why energy distribution needs to be identified based on the ATFs defined in the previous stage. These ETFs are determined by the different energy flows that exist inside the system. Energy transport, storage, and conversion are the functions that system components have to execute depending on the type of input and output energy they get. It is important to identify the nature and the perimeter of these energy flows to characterize the behavior of the components that will execute a given function. To develop this stage, the same set of five steps is used as follows.

3.2.1 EC Specify

The first step of this stage is to identify the incoming and outcoming energy flow of the Basic Functions that are already grouped as ATFs. So, it is necessary to identify the type and nature of the different energy flows. These characteristics determine the type of manipulation that is required for a specific function. For the study case, some of the energy flows that go in and out of the BFs are shown in Table 5.6.

Table 5.6. Energy flows for the welding workstation BF.

Function	Input flow	Output flow
Position the parts to be welded on the holding area	Chemical/Electrical	Mechanical
Fix the parts to be welded to the holding area	Any type	Mechanical
Position the holding area in relation to the robot/storage rack	Electrical	Mechanical
Release the welded parts from the holding area	Any type	Mechanical

3.2.2 EC Design

Based on the type of energy flow that goes through a function, it is possible to determine what kind of ETF is needed to ensure a proper energy treatment. The application method defines the possible type of energy processing that the function must perform: convert, transform, or transport. In the welding workstation, the type of ETF can also be found in table 5.7. For some cases, there is no direct energetic treatment that provides the expected output flow from the input energy. In those cases, it is necessary to classify the different possibilities to accomplish that treatment. For example, in some applications, it would be better to pass through one conversion and one transformation rather than a single conversion due to the context of the design problem.

Table 5.7. ETFs for the welding workstation.

Function	ETF
Position the parts to be welded on the holding area	Conversion
Fix the parts to be welded to the holding area	Conversion/Transformation
Position the holding area in relation to the robot/storage rack	Conversion
Release the welded parts from the holding area	Conversion/Transformation

After that general definition of the different possible solutions, it is necessary to consider the technical constraints related to every BF to define the criteria to choose the most suitable solution. To do so, the different solutions need to be sorted out, as shown in Figure 5.8.

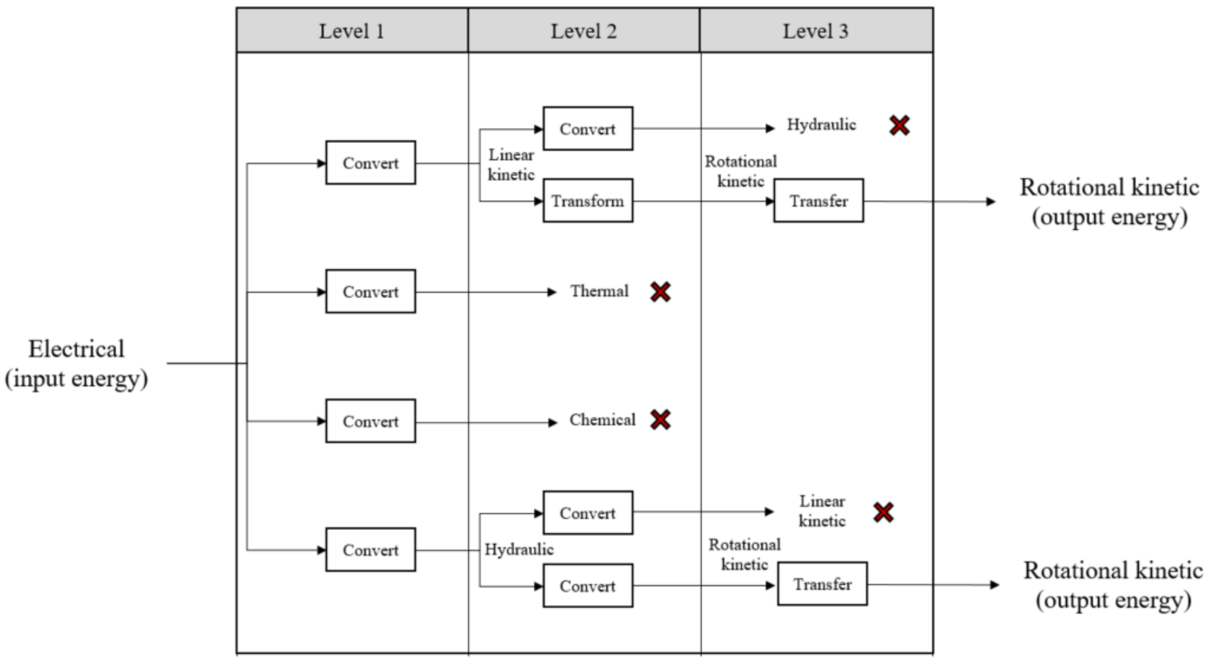

Figure 5.8. Decision diagram for the most suitable solutions.

3.2.3 *EC Model*

Using the already defined ETF for the BF, it is necessary to represent it through a graphical formalism. The diagram shown in Figure 5.9 is used to illustrate the input and output flow of a BF of the study case. All ETFs must show the interactions with the others to detect all the energy distribution inside the system.

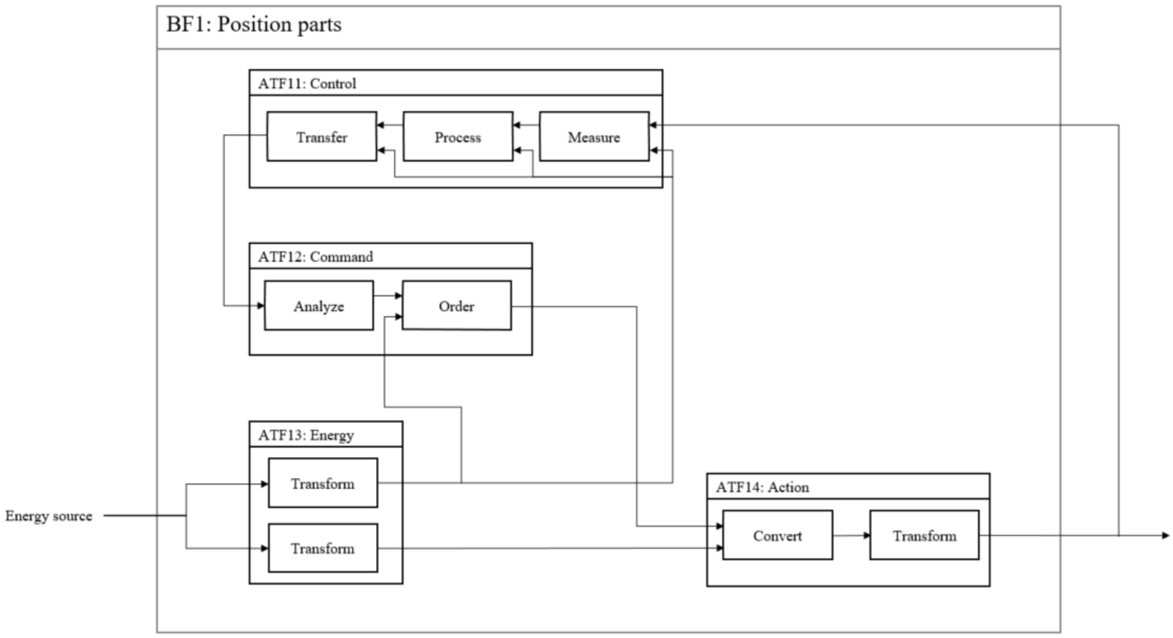

Figure 5.9. Example of the ETF model of the Basic Functions in the welding workstation.

3.2.4 EC Evaluate and Optimize

To evaluate and optimize ETF is necessary to evaluate the exhaustiveness of the energy distribution in the system. To do so, the application method is to evaluate that for every Basic Function, all types of energy have been considered in the input flow and the output flow. It is necessary to discuss the possibility of carrying out a digital simulation (1D simulation) at this stage. As the geometric and topological data are not yet available, it consists of simulating the system's energetic behavior and making sure that it is in conformity with the specifications. To go deeper into the energetic characterization, it is possible to apply the quantification of the energy flows based on the functional modeling of [Malmiry et al. 2016].

3.2.5 EC Validate

Finally, to validate the ETF is necessary that they correspond to the requirements defined by the customer. So, the same criteria based on time, cost, and performance are used to ensure that the energetic model of the Operating System meets the requirements. For the study case, the model of the ETF of the BF does not present any issue related to the requirements, so it is possible to continue to the next stage.

3.2.6 Summary

The introduction of ETF to the product modeling allows the designer to have a clear perspective of all the energy manipulations that the system executes and how they add to the overall production process. Based on this, it is possible to characterize the type of technical solutions needed to ensure each Basic Function. At this point, the functional architecture of the system model is almost completed based on the three elements that have been fully defined:

- BF: functional need to achieve the mission.
- ATF: functional behavior of the BFs to meet the need and to identify the system's internal energy requirements.
- ETF: energy behavior of the ATFs described in the form of a continuous energy transformation chain.

Components selection is made based on this model, and it is explained in the following section. Components are the final elements (physical and nonphysical) of the Operating System that execute the BFs. All the components that do not exist in the Current System need to be defined using ETF. These energetic functions are the input value to a set of technical solutions classified based on the type of energetic manipulation. So, for example, if it is required to convert a flow of electric energy into a flow of mechanical energy, an electric motor or an electric actuator would execute that type of energetic treatment.

This section has shown the general product modeling process that is supported by the defined design framework. As shown, the method becomes systematic but does not set aside the characteristics of the product. This way, it is possible to have a structure and organized design project that considers all the design phases, giving the designer the tools needed to address any design problem. It is also necessary to specify here that the passage from the customer's needs to the components is done progressively and logically by following the principle of least commitment (advancing step by step by relying on robust and not hypothetical input data). This approach's contribution relies on two aspects: identifying the client's real needs based on the current state of the production system and the definition of components based on an energetic approach using the behavior of the functions, energy flow through components, and their structure.

3.3 Components Selection (CS)

The selection of components is made using ETFs and standardized catalogs classified by energy treatment. It should be specified here that this classification is not taken from general catalogs but proposed by this research project because it is more relevant than the classification by technological family and is part of the continuity and logic of the design process (see Appendix 2 for the complete classification). For specific components that have not been standardized, it is necessary to define all its parameters. These "non-standard" components are essential when designing a system (e.g., the frame or chassis). Due to their singularity, the design of these components will have to be pursued in a detailed way until all the data necessary for their manufacture are known. It is important to note that this mechanically and considerably increases the cost and the development time of the system. That is why it is always preferable to choose a standardized component as far as possible. First is necessary to identify the components available to complete the mission from the ETFs list. Then, define those components' nature and perimeter using the energy flows. With the energy treatment necessary to perform the ATFs, it is possible to choose from catalogs the components that meet these functions by prioritizing incoming energy types that are more easily accessible in the workspace.

3.3.1 CS Specify

The first step of this stage is to identify the possible families of components that allow the ETFs' incoming and outcoming energy flows. So, it is necessary to recover from the Operating System model the type and nature of the different energy flows and treatments and then use that information to check the possible solutions from Table 5.8.

Table 5.8. Matrix of technical solutions based on energy flow (extract).

		Output				
		Kinetic	Hydraulic	Pneumatic	Thermal	Electrical
Input	Kinetic	Mechanisms	Hydraulic pumps	Pneumatic pumps	Friction, impact	Electric generators
	Hydraulic	Hydraulic actuator	Valves	-	Friction	Electric generators
	Pneumatic	Pneumatic actuator	-	Valves	Friction	Electric generators
	Thermal	Turbines and thermal engines	-	-	Heat exchangers	Thermoelectric, thermionic, and magneto-hydrodynamic converters
	Electrical	Electric motors, piezoelectricity	-	-	Joule effect (electrical resistances)	Electrical transformer

3.3.2 CS Design

Based on the type of energy flow that goes through a function, it is possible to determine what kind of component is needed to ensure a proper energy treatment. Based on the possible solutions chosen in the previous step, with the different levels of energy treatment and the criteria based on every BF's technical constraints, it is possible to choose the final conceptual solution for the design problem. In general, this step consists of:

- Choosing the component family associated with each ETF (from the work done in the previous step),
- Sizing the component that meets the energy specificities of the ETF and the Technical Constraints that are applied to it (see the associated BF and the matrix link)
- Ensure technological consistency (rationalization of the technologies used) and compatibility between all the components

In some cases, it is possible to use preexisting components from the Current System. In the case of the Case study, the worker must be kept as part of the system as part of a constraint defined by the client. In that case, some tasks of the Operating system will continue to be executed by the worker.

3.3.3 CS Model

Using the already defined ETF for the BF, it is necessary to represent it through a graphical formalism. The organic architecture is based on the same formalism used for the ETFs in the functional architecture. It is just necessary to substitute each ETF with its corresponding component. This shared formalism between the two architectures contributes significantly to the traceability of design data while improving their readability. The diagram shown in Figure 5.10 illustrates the input and output flow of the BF of the study case. All ETFs must show the interactions with the others to detect all the energy distribution inside the system.

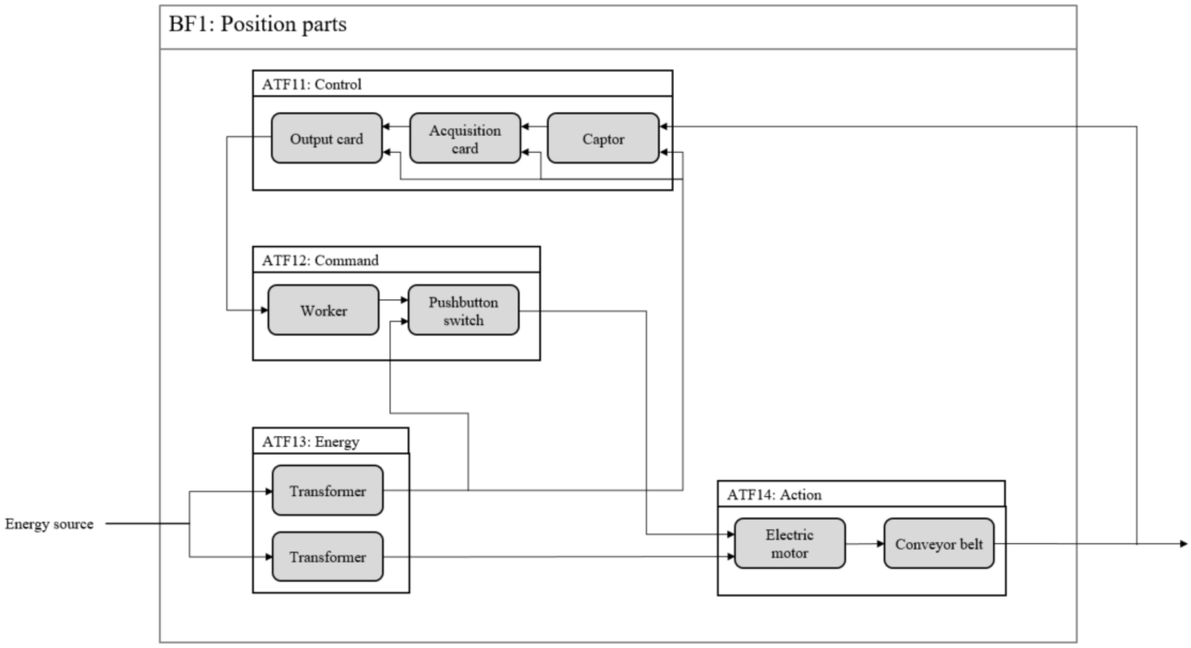

Figure 5.10. Example of the components model of the Basic Functions in the welding workstation.

3.3.4 CS Evaluate and Optimize

To evaluate and optimize ETF is necessary to evaluate the exhaustiveness of the energy distribution in the system. Generally speaking, it is a matter of ensuring that each component chosen will fulfill its role to carry out the mission. This step relies heavily on numerical simulation, which will be implemented in all necessary fields (e.g., mechanical, thermal, acoustic). To do so, the application method is to evaluate that for every Basic Function, all types of energy have been considered in the input flow and the output flow. That can also show dangerous situations that have been ignored related to the proximity of an energy flow to a worker. In the example, all types of energy were considered to define ETF.

3.3.5 CS Validate

Finally, to validate the ETF is necessary that they correspond to the requirements defined by the customer. This activity is the same as for the ATFs and ETFs: it is the object to validate the changes. Thus, this step also consists in making a decision, in choosing the whole of the components of the system starting from the elements of information resulting from the activities EC Design and EC Evaluate and Optimize. So, the same criteria based on time, cost, and performance are used to ensure that the energetic model of the Operating System meets the requirements. For the study case, the model of the ETF of the BFs does not present any issue related to the requirements, so it is possible to continue to the next stage.

In conclusion, this is the last stage of the product modeling before passing to Detail Design. The production system model is fully defined, and all its characteristics have been checked to fulfill customer’s needs. There will be standard components that will not need any definition steps, but other components need to be dimensioned during the detail design phase.

4. Safety integration

As said in Chapter 1, human factors and safety are vital elements for production systems design due to the influence of workers' actions and behavior in the system's overall performance. Identify safety risks as early as possible during the design phases is a requirement for a general design framework. That identification must be performed using the system's information available during the design process. For that task, some research works have use energy-based product models as dedicated tools for safety assessment. In the approach proposed by [Gomez Echeverri et al. 2020], the energy-based system model is multi-purpose because it fully defines the system's behavior and provides the required information for analyzing human factors and safety. The integration of decision-making tools can also be adapted to other types of expertise, such as sustainable design.

The proposed method by [Gomez Echeverri et al. 2020] can be adapted to work with the proposed design framework discussed in this manuscript. The input values and information needed to perform the safety analysis are complete after the Components Selection step. Based on the model of the Operating System and the properties of its components, it is possible to use CAD software to evaluate the level of risk for a human worker inside the system. In the following paragraphs and subsections, the method of application is explained.

The functional architecture and the anteriority constraints are used to apply a first filter of the potentially dangerous activities for the workers. That filter is needed to simplify the safety assessment and not consider non-human component interactions. To determine those situations, simultaneous activities of workers and components are identified. Then, to qualify the hazards associated with each potentially dangerous situation, a second filter needs to be applied to determine the interactions between human workers and the components. The quantification of the hazards uses the numerical values of the energy flows interacting with the worker to compare them with the limit values for human interaction. The calculated value of the energy flow represents the danger level for an operator and determines the severity compared with the limit values.

A volume of influence is defined as the physical space where one or more properties of the components can act. Due to their importance for risk identification, seven types of volumes of influence have been defined: six related to energy types (potential, kinetic, thermal, chemical, radiation, and electrical) and one related to geometric and material aspects (structure). It is important to emphasize that the structural VI is the basic volume for the other types of VI because the characteristics allow determining all the others (Figure 5.11). The hazardous area (geometry) is defined by the spaces occupied at each stage studied (static image sequence) by the areas of influence of equipment and the operator (simplified modeling).

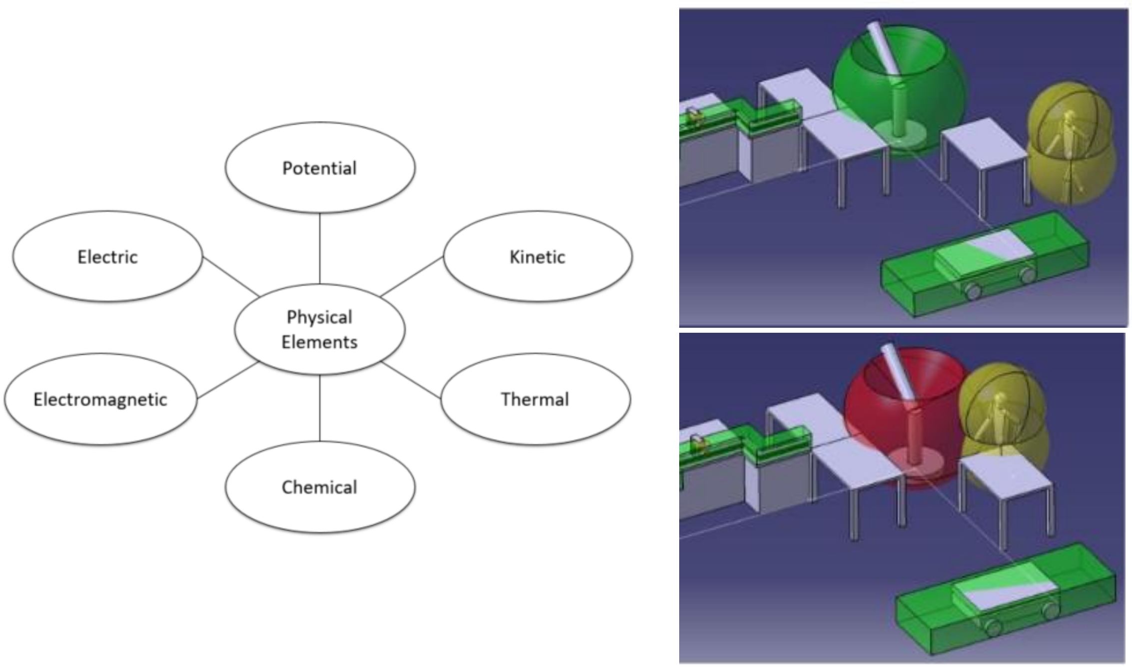

Figure 5.11. Volumes of influence [Gomez Echeverri et al. 2020].

4.1 Identify the operating steps

This first step of the safety analysis aims to make a first filter of the potentially dangerous activities for the operator in order to simplify the study of the process so as not to take into account all the operating steps (interactions component/component, human/component, human/human) but which can generate a risk for the safety of the operator

- List the components constituting the production system. That allows to know all the types of elements that will be treated by the method, essential information for the continuation of the process of detection of risks.
- Model the layout of the components to have a representative model of the production system.
- Extract the steps in which the operator can potentially act at the same time as one or more modules or operators

In this step, the user must use the production line to be studied and determine the situations where there is a simultaneous activity of one or more operators and one or more modules.

4.2 Qualify the hazards

This step aims to define the hazards associated with the potentially dangerous operations for the operator in each situation identified in the previous step. The volumes of influence (VI) will be identified and attributed to each module to make the risk analysis.

- Identify the VIs associated with the modules constituting the operating steps. This identification is made with the help of the definition of the VIs, of which there are seven different types according to the nature of the module.
- To represent the geometry of the VI according to the situation of work
- Position the geometries of the VIs in relation to each other for each work situation to have the spatial distribution of all the VIs present in the production cell.
- Identify the modules whose VIs intersect and qualify the types of danger

From the geometrical model of the functional modules and VI, the user must identify the situations where the VI of the operators intersect with the VI of the modules to make a second filter of the potentially dangerous states for the human. The interest is only in the interactions human/component or human/human in the case of multiple operators working at the same place.

4.3 Quantify the types of hazards

The quantification step uses the numerical values of the properties of the VIs to compare them with the limit values of interaction with humans.

- To calculate the value of the parameter representing the level of danger of each VI cut for that of an operator. The user must calculate the numerical values of each of the characteristics of the modules for each VI that cuts the VI of an operator, according to the properties listed during Task Clarification.
- Determine the severity for each module and work situation. The user must compare them with the limit values in Appendix 3 and determine their severity level from the calculated values.
- Quantify the associated risk level for the whole configuration. This step allows the user to compare several configurations to determine the different severity levels and their changes according to the distribution of the modules.

4.4 Filter the steps with a negligible severity level

This step is used to make a final filter of the potentially dangerous situations based on the value found in the previous step. If the severity level is negligible or zero for a given work situation, it must be removed from the list.

This method's contribution relies firstly on the arrangement and interactions between the different elements that conform the design process, and secondly, on the exploitation of that structure to obtain the required information for a successful design project. That information is obtained and treated from the early steps of the process by evaluating the environment and the current state of the production system and then by characterizing its expected behavior. The three elements that have been introduced in the literature review (design phases, product model, and design reasoning activities) have not been fully integrated into any of the existing design methods and theories, that is why the proposed approach uses an energy-based product model, which allows the integration of those elements from the cost, time, performance, and safety viewpoints.

4.5 Modify the system model

After identifying the potentially dangerous situations, the modification of the system model is required to protect the workers' safety. In the case study, two functions of protection have been added to the functional architecture of the system. In Figure 5.12, the added functions can be seen in the discontinue blue rectangles. It is important to note that those new functions are defined for a nominal operation without considering the malfunctioning of any component because that is the functional case addressed by [Gomez et al. 2020].

However, it is also possible to apply other analytical methods to identify dangerous situations related to an abnormal operation, such as FMEA and FMECA [Bouti & Kadi 1994] [Bertolini et al. 2006]. According to [Lipol & Haq 2011], Failure Modes and Effects Analysis (FMEA) and Failure Modes, Effects, and Criticality Analysis (FMECA) are methodologies designed to identify potential failure modes for a product or process before the problems occur, to assess the risk. Ideally, FMEA's are conducted in the product design or process development stages, although conducting an FMEA on existing products or processes may also yield benefits. The FMEA team determines, by failure mode analysis, the effect of each failure and identifies single failure points that are crucial. It may also rank each failure according to the criticality of a failure effect and its probability of occurring. The FMECA is the result of two steps:

- Failure Mode and Effect Analysis (FMEA)
- Criticality Analysis (CA)

The case presented in Figure 5.13 represents in discontinue red rectangles the protection functions for an abnormal operation of the system model of the welding workstation. The following section concludes the chapter by discussing the case study results and analyzes the proposed method as part of a general design framework.

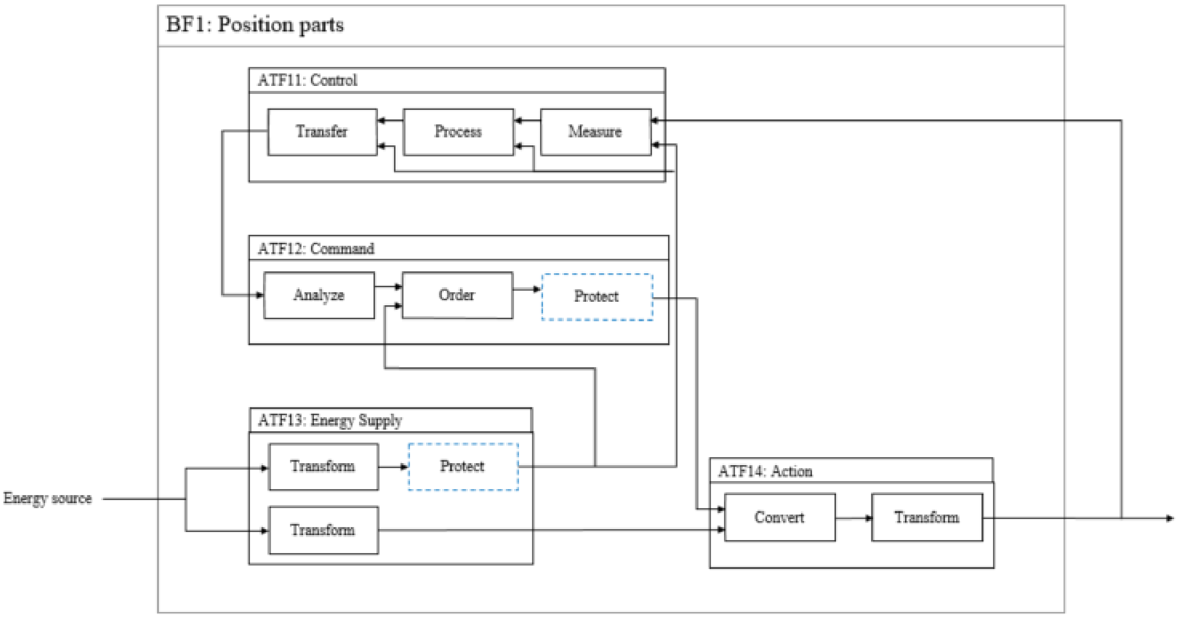

Figure 5.12. Safety measures for nominal operation.

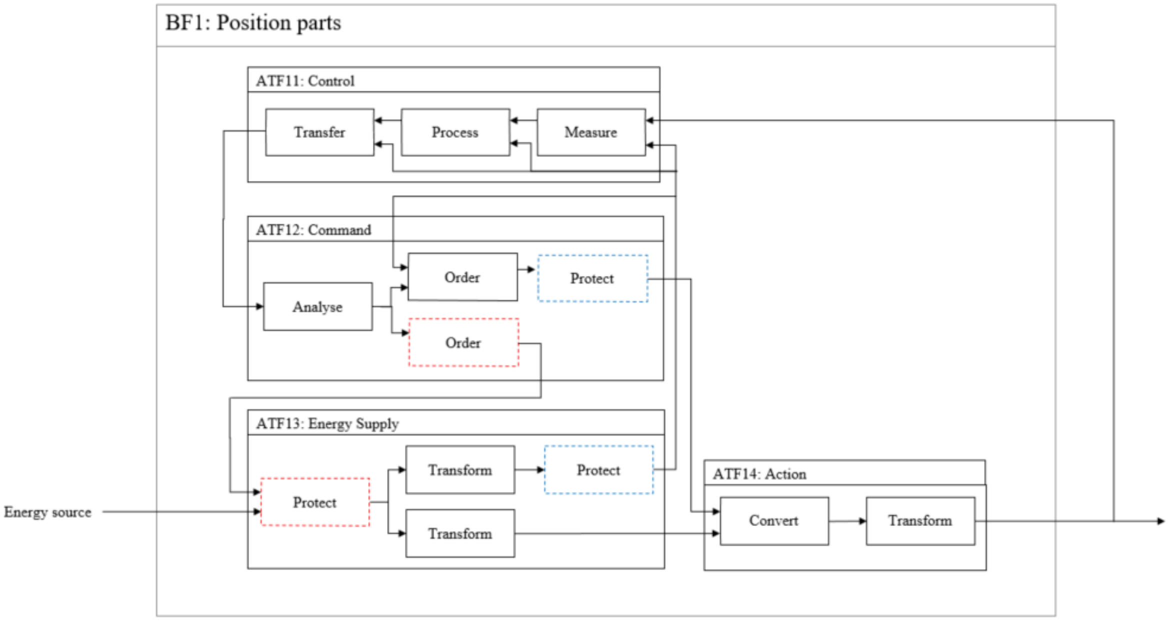

Figure 5.13. Safety measures for abnormal operation.

5. Results and discussion

The use of the system modeling approach, backed by a defined design framework, has been demonstrated in this chapter. The sequence of treatment of the study items is provided logically and systematically in this case study. The method is systematic when applying the different design phases and steps, and it contributes to the development of the system model and all the properties and characteristics of its components. The contribution of this technique is based on determining the client's real demands based on the existing condition of the production system and component definition based on an energetic approach employing function behavior and energy flow through the component structure. The final chapter of the manuscript discusses the possibilities for future research on this topic.

As has been demonstrated, there are numerous design theories for designing a production system, each of which employs a different set of principles for the design process. Some of them are more concerned with the project itself, employing a tight framework of sequential activities, while others place a greater emphasis on product qualities to solve the design problem, leaving the project framework to the side. Because there is not a general design theory that takes into account project planning, product characterization, and design reasoning, the concept of developing an integrated method that combines those three parts to design more reliable production systems emerges.

In the end, the method makes use of only three different types of formalism: Formalism of the existing system (entity-relation model structured according to time); Formalism of the customer's need (mind maps and link matrix); Architecture formalism (entity-relationship model applied to BF, ATF, ETF, and EC). Those three formalisms simplify the modeling of complex systems and provide the required information for the design team during the final solution development.

The goal of this chapter was to present the work done on this study topic by presenting a design method for production systems. This method takes some of the key ideas from other design theories and combines them to emphasize the formalization of the client's desire to produce a production system that fulfills their needs. One of the contributions of this method to contemporary design theories is the energetic approach BES utilized to shift from fundamental functions to components.

Chapter 6: Conclusions

Abstract

This chapter concludes the manuscript by first summarizing the general objectives defined for the research project and the obtained main results. Those objectives guided the development of the proposed design method by contextualizing the research issues and the literature review. Then, the chapter goes through the contributions made regarding productions systems design, project planning, system modeling, and safety integration to the design process. Those contributions are explained based on a review of the proposed design approach and are compared with the design requirements already developed in other design research works. Also, it is reviewed how existing design tools can be used alongside the proposed method based on the obtained information during each step of the design process. Finally, the chapter concludes by discussing the general perspectives of the research project and how other key performance indicators cloud be integrated into the proposed design method.

1. Issues and fundamental research questions

This first section summarizes the general research objectives and methodology used to develop the proposed design method. The objective is to recall those objectives and evaluate if they have been accomplished with the results of this research work. As presented in chapter 1, the goal of this research project was to propose a multi-criteria design framework to design complex, multi-technology production systems that meet design requirements while also being flexible enough to incorporate other requirements such as human safety or sustainability. Safety requirements were used as the decision-making criteria in this work to demonstrate integration throughout the design process.

The general research objective was summarized by the question: How to design a production system integrating the safety of operators while respecting all design objectives in terms of time, cost, and performance? Based on that question, three scientific issues were defined in order to address that objective:

- Issue 1: How to define a design framework to consistently manage the design process, system modeling, and design reasoning?
- Issue 2: How to define a methodology for analyzing the risks related to the safety of the production system workers?
- Issue 3: How to establish a connection between design data and risk analysis tools to consider the safety of operators as early as possible in the design of production systems?

Those scientific issues were classified into three broad categories: design methodology, safety risk identification, and safety integration in design. While the first two aspects required independent analysis, the third one was based on the compatibility of the two others.

The first issue was related to the various components of design theories and methods. It was necessary to search and analyze various design approaches to determine their applicability and define the various design phases, activities, and models. Those elements proved to be sufficiently adaptable to allow for integrating various complementary design approaches and decision-making tools.

The second issue sought to define a generic risk analysis tool capable of considering the effect of an industrial environment on human safety. The purpose was to describe a risk identification approach that can be used during the early stages of a production system's design process. The compatibility of the risk and design approaches was considered based on where and when those approaches were applicable and how early in the design process the required information was available.

Finally, the third issue established the thesis's primary objective. The integration of risk analysis and production system design needed a broad framework that allows design flexibility while maintaining the final solution following the design requirements and constraints.

All of these issues have been addressed in this project as part of the research methodology. In the following subsection, the results of the research work are recalled as a synthesis of all the elements presented in this manuscript and how they relate to the research objective and issues.

2. Contributions

The research issues have been addressed using comprehensive literature reviews (see chapter 2) and the application of a case study developed alongside the proposed methodology. A particular focus of the literature reviews was on the investigation of system models, function modeling, and safety integration tools proposed in disciplinary and interdisciplinary design approaches.

2.1 Regarding productions systems design and safety integration

As discussed, three main elements intervene during any design project: requirements, design process, and tools (Figure 6.1). These elements are identified and applied by the design team to develop the final solution for the design problem. The design process was addressed in Chapters 3 and 4, while the integration of the design tools into the design process was discussed in Chapter 5. The design requirements have been discussed by [Cochran et al. 2001], and their impact on the other two elements is discussed in subsection 2.2 of this chapter.

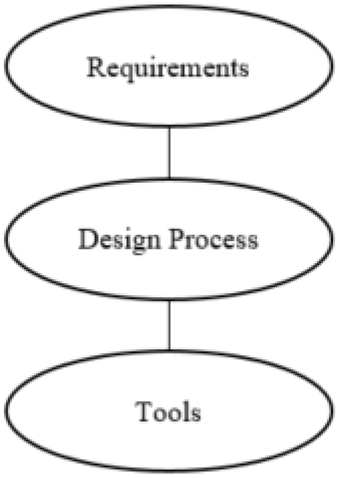

Figure 6.1. Working elements of a design project.

To address the first research issue related to the design process and structure, a general framework has been proposed based on the Systematic Design phases, the product/system modeling of FBS, and the iterative nature of the activities from design reasoning. The development of this framework has been discussed in Chapters 3 and 4. That framework is represented in a matrix-like model (Figure 6.1), which introduces a different understanding of the design process. This representation provides specific tools and solutions for every aspect of the design process. The differentiation of every design activity for every design step allows the integration of other tools in very specific moments of the process, giving increased flexibility to the proposed method depending on the design problem. For example, in the Evaluate and Optimize activity, it is possible to integrate different criteria to evaluate an intermediate solution based on the client's needs.

The second research issue was addressed by identifying safety integration approaches and tools compatible with the proposed design framework. Those approaches and tools were classified depending on the type of element they represented and their required information. That information influenced the definition of the system modeling by determining the characteristics and properties needed to be defined to be able to use the safety approaches and tools. The identification of the elements to consider for a safety analysis has been discussed in Chapters 2 and 4.

The third and final issue was addressed by the definition of when the safety approaches and tools could be applied in the design process and the iterative nature of the design reasoning activities. That allowed to consider the safety aspects of the production system as part of the design process. That integration was made using the design reasoning activities, which, how has been mentioned, can be adapted following the design needs. This integration has been discussed in Chapter 5.

The system modeling of the approach was defined by the elements and information needed at the different steps of the design process related to the design and safety objectives of the project. The characterization of different elements integrated into the system model makes possible the consideration of other key performance indicators using a unique model.

The application of the proposed method to a welding workstation provided the required feedback to validate the approach. The study case was a design process based on a preexisting production system, which corresponds to the majority of the cases of standard design. In the case of innovative design, the method can also be applied, changing the starting point of the system modeling. That flexibility complies with the research project's design objectives by providing a general framework applicable to most of the design problems.

Because the method was applied to a real-world study case, it was possible to identify and correct some of the framework's shortcomings. In order to design highly complex systems, the method may require the use of a large number of diagrams, which may make it difficult to employ this technique. That is one of the directions in which future research initiatives should be directed to complement the method.

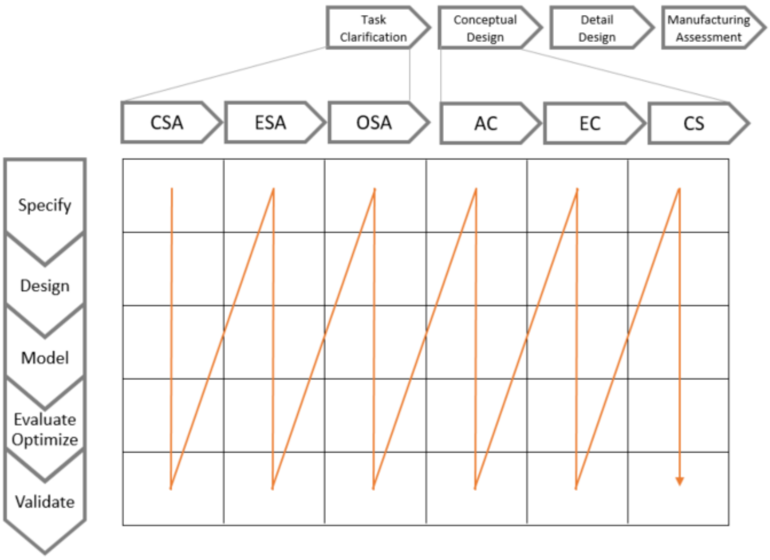

Figure 6.2. Matrix-like representation of the proposed design framework.

2.2 Design process requirements

Several frameworks have been developed to connect low-level decisions to system-level objectives. These frameworks frequently link diverse production design and development tools to a production organization's objectives. [Gilgeous & Gilgeous 1999] provide a framework that takes into account four high-level production system performance objectives (quality, cost, delivery, and flexibility) as well as eight tactical initiatives that all contribute to the achievement of each performance objective. [Hopp & Spearman 2011] created a hierarchy of production objectives, starting with the goal of "high profitability." As depicted in Figure 6.2, this hierarchy shows that ideal production system performance is subject to trade-offs. It also demonstrates that one design feature, a fast cycle time (throughput time), relates to cost reduction as well as improved customer service. These techniques do not establish a strong design relationship between strategic objectives and operational ways to achieve them, nor do they state the means to achieve the specified objectives. The proposed approach defines those strategic objectives during Task Clarification and the operational ways to achieve them during the Conceptual Design phase.

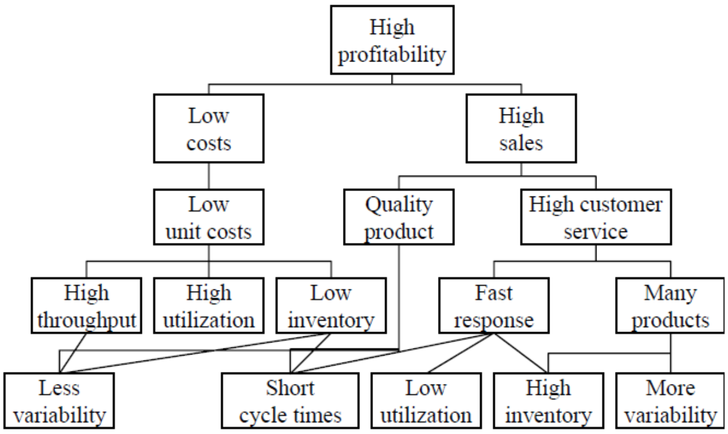

Figure 6.3. Hierarchy of production objectives [Hopp & Spearman 2011].

The Manufacturing System Design Decomposition (MSDD) proposed by [Cochran et al. 2001] states that the most important condition for any manufacturing system is to maximize long-term return on investment. Long-term return on investment (ROI) in this context refers to a system's whole life cycle rather than simply the next few years. This approach is based on Axiomatic Design and uses Functional Requirements (FR) and Design Parameters (DP) to define the design objectives. In Figure 6.3, maximizing customer satisfaction (DP-11) is proposed as a strategy for increasing revenue. This DP was then deconstructed further based on the critical performance aspects of manufacturing systems that impact customer satisfaction: compliance quality (FR-111), on-time delivery (FR112), and low lead-time (FR-113). The specified method of obtaining high-quality guarantees that production processes deviate from the objective as little as possible (DP-111). Instead of relying on final inspection to avoid the shipment of defective components, DP-111 focuses on process improvement. At this level of design (shown visually in Figure 6.3 by arrows), attaining compliance quality (DP-111) is important for increasing customer satisfaction. Variation in quality and the production of defects makes system output unpredictable, which has a negative impact on FR-112, "Deliver products on time," and necessitates the production of additional parts to replace these defects, which has a negative impact on FR-113, "Meet customer anticipated lead time." High quality of compliance is necessary to mitigate the influence of DP-111 on the predictable delivery and lead time of a manufacturing system design.

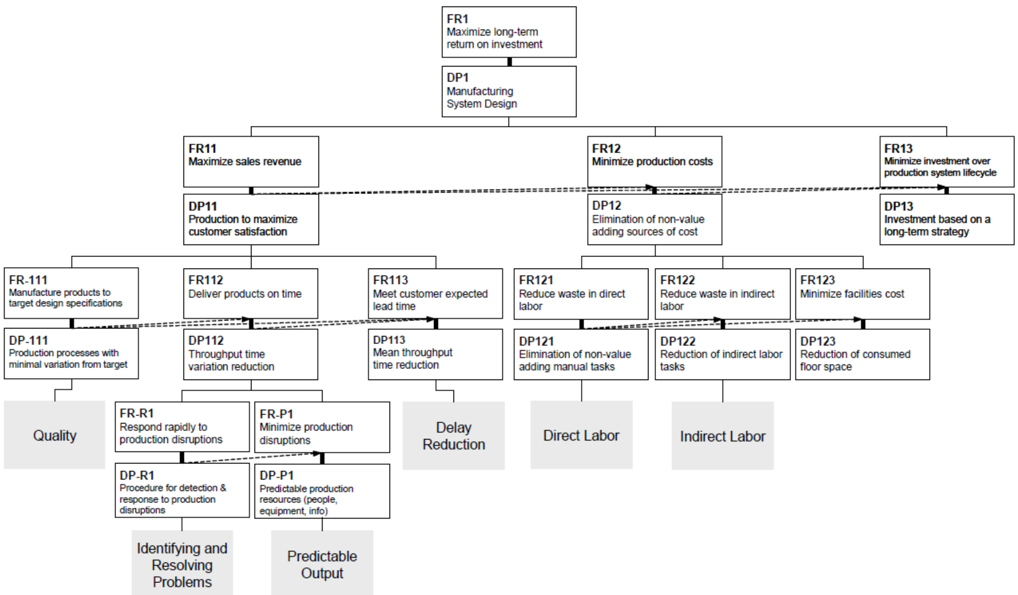

Figure 6.4. Upper levels of the MSDD [Cochran et al. 2001].

Observing the design objectives and how this approach proposes their definition, it is possible to say that how they connect low-level decisions to system-level objectives is based more on a higher level of granularity of the client's company. In the case of the proposed approach, the level of granularity defines the perimeter of the design project and avoids the modeling of system aspects that are not relevant to the design problem at hand. It is also possible to say that multiple solutions can be found depending on the level of granularity. In general terms, the design objectives proposed by [Cochran et al. 2001] define the same design requirements addressed by the proposed method. However, the proposed approach provides more technical details and specifies the design process based on the client's needs.

Nevertheless, the requirements in terms of quality, delays, and problem resolution defined by Cochran are entirely compatible with the proposed design method and can be addressed by it. Moreover, the introduction of other design requirements related to the safety of operators enriches the catalog of requirements considered by [Cochran et al. 2001]. The following section concludes the chapter and the manuscript by discussing the perspectives for this research project based on the obtained results and the possible applications of the method.

3. Perspectives

It is possible to categorize research perspectives according to three main categories: general perspectives, data collection and analysis, and model extensions.

As a starting point, it would be interesting to propose the development of a software tool capable of generating the set of possible configurations of the system model final solution based on the identified BF and technical constraints. Even if the whole method is not yet possible to fully automatize, the Conceptual Design phase presents elements that can be translated into an algorithm and be performed by a computer. As a result, it can assist the design team in the development of their system models after the Task Clarification phase.

Also, integrating other KPIs related to sustainability or production optimization can be an interesting perspective for the method. That integration can be made similarly to the safety integration presented in Chapter 5 by exploiting the flexibility that provides the design reasoning activity of Evaluate and Optimize at every step of the process. That approach would increase the field of application of the method and open the door for other methods or tools to be integrated as part of the design process. That brings the second point of view, which is data collection and analysis.

The proposed design method provides a general solution to the development of a design project and has been tested in a study case. However, it is necessary to determine how it is applied by different design teams to identify how it correlates to the user's needs. In that regard, it would be advantageous to follow one or more development projects from start to finish to collect observations and data for future use.

Several options exist in terms of model extensions, depending on the available data and user requirements. It would be interesting to expand the design reasoning activities to the other two phases of the proposed method. Even if the application of the Detail Design and Manufacturing Assessment phases is fairly straightforward with the current methods, it can be a form of standardizing the design methodology using common elements among the different phases.

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Appendices

Appendix 1: Heuristic chart of Basic Functions for the welding workstation.

Life cycle phase	Functional case	Basic Functions	Performance level	Unit	Target value	Tolerance
Operation	Welding	Position the parts to be welded in relation to the system	Operating time	s	A1	-
			Part reference	-	21	-
			Degrees of freedom	-	x y z	-
			Displacement	mm	0	±10
			Weight	kg	See reference	-
		Fix the parts to be welded to the system	Operating time	s	A2	-
			Part reference	-	21	-
			Degrees of freedom	Degrees of freedom	0	-
			Weight	kg	See reference	-
		Move the parts to be welded from the storage rack to the holding area	Operating time	s	A3	-
			Part reference	-	21	-
			Degrees of freedom	-	x y z	-
			Displacement	mm	2000	-
			Weight	kg	See reference	-
		Position the parts to be welded on the holding area	Operating time	s	A4	-
			Part reference	-	21	-
			Degrees of freedom	-	x y z	-
			Displacement	mm	0	±0,1
			Weight	kg	See reference	-
		Fix the parts to be welded in relation to the holding area	Operating time	s	A5	-
			Part reference	-	21	-
			Degrees of freedom	Degrees of freedom	0	-
			Weight	kg	See reference	-
		Release the parts to be welded from the system	Operating time	s	A6	-
			Part reference	-	21	-
			Degrees of freedom	-	x y	-
			Displacement	mm	0	±10

			Weight	kg	See reference	-
		Position the holding area in relation to the welding robot	Operating time	s	A7	-
			Part reference	-	21	-
			Degrees of freedom	-	x y z	-
			Displacement	mm	0	±0,1
			Weight	kg	See reference	-
		Fix the holding area to the base of the welding robot	Operating time	s	A8	-
			Part reference	-	21	-
			Degrees of freedom	Degrees of freedom	0	-
			Weight	kg	See reference	-
		Release the holding area from the base of the welding robot	Operating time	s	A9	-
			Part reference	-	21	-
			Degrees of freedom	-	x y	-
			Displacement	mm	0	±10
			Weight	kg	See reference	-
		Position the holding area in relation to the storage rack for the welded parts	Operating time	s	A10	-
			Part reference	-	21	-
			Degrees of freedom	-	x y z	-
			Displacement	mm	0	±10
			Weight	kg	See reference	-
		Fix the welded parts to the system	Operating time	s	A11	-
			Part reference	-	21	-
			Degrees of freedom	Degrees of freedom	0	-
			Weight	kg	See reference	-
		Release the welded parts from the holding area	Operating time	s	A12	-
			Part reference	-	21	-
			Degrees of freedom	-	x y	-
			Displacement	mm	0	±10
			Weight	kg	See reference	-
		Move welded parts from holding area to storage rack	Operating time	s	A13	-
			Part reference	-	21	-

			Degrees of freedom	-	x y z	-
			Displacement	mm	2000	-
			Weight	kg	See reference	-
		Position the welded parts in relation to the storage rack	Operating time	s	A14	-
			Part reference	-	21	-
			Degrees of freedom	-	x y z	-
			Displacement	mm	0	±10
			Weight	kg	See reference	-
		Release the welded parts from the system	Operating time	s	A15	-
			Part reference	-	21	-
			Degrees of freedom	-	x y	-
			Displacement	mm	0	±10
			Weight	kg	See reference	-

Appendix 2: Matrix of technical solutions based on energy flow.

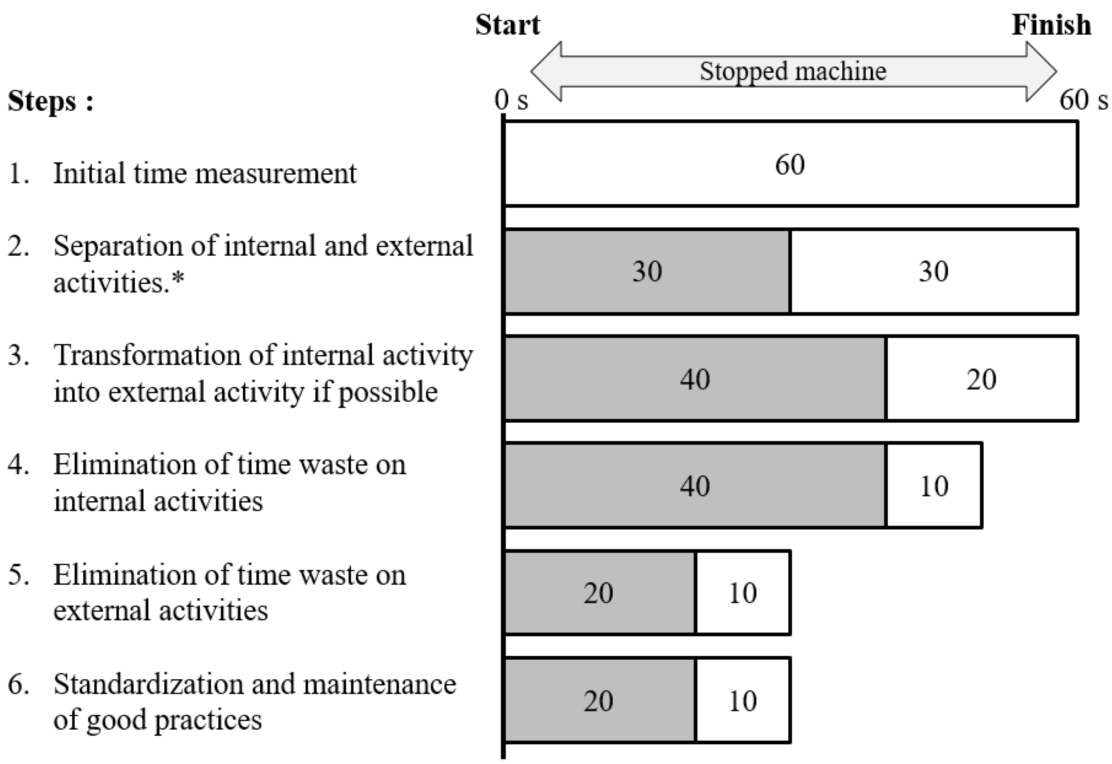
		Output energy										
		Kinetic	Hydraulic	Pneumatic	Thermal	Electrical	Chemical	Electromagnetic	Nuclear	Electrostatic	Elastic	Gravitational
Input energy	Kinetic	Mechanisms	Hydraulic pumps	Pneumatic pumps	Friction, impact	Electric generators	-	-	-	Friction	Springs	Height
	Hydraulic	Hydraulic actuator	Valves	-	Friction	Electric generators	-	-	-	-	-	-
	Pneumatic	Pneumatic actuator	-	Valves	Friction	Electric generators	-	-	-	-	-	-
	Thermal	Turbines and thermal engines	-	-	Heat exchangers	Thermoelectric, thermionic and magnetohydrod ynamic converters	Thermolysis	Incandescence	-	-	-	-
	Electrical	Electric motors, piezoelectricity	-	-	Joule effect (electrical resistances)	Electrical trransformer	Electrolysis	Discharge, electroluminesc ence	-	Electrical conductor	-	-
	Chemical	Combustion	-	-	Combustion / fermentation	Accumulators, batteries	-	Chemiluminesc ence	-	-	-	-
	Electromagnetic	-	-	-	Solar radiation sensors	Photovoltaic converters	Photochemistry, photosynthesis	-	-	-	-	-
	Nuclear	-	-	-	Nuclear reactors	-	-	-	-	-	-	-
	Electrostatic	-	-	-	-	Electrical conductor	-	-	-	-	-	-
	Elastic	Springs	-	-	-	-	-	-	-	-	-	-
	Gravitational	Height	-	-	-	-	-	-	-	-	-	-

Appendix 3: Table of limit values

Level of risk	Type of VI							
	Potential	Kinetic	Thermal	Chemical	Acoustic	Electromagnétique	Nuclear	Electric
Negligible	[0 ; 1] J	[0 ; 10] N	[-- ; 44] °C	1 or 0	[0 ; 50] dB	[1 ; 700] cd/m^2	[0 ; 0] Gy	[0 ; 0,5] mA
Low	[1 ; 2] J	[10 ; 300] N	[44 ; 47] °C		[50 ; 70] dB	[700 ; 1000] cd/m^2	[0 ; 1] Gy	[0,5 ; 5] mA
Medium	[2 ; 3] J	[30 ; 50] N	[47 ; 51] °C		[70 ; 80] dB	[1000 ; 2000] cd/m^2	[1 ; 3] Gy	[5 ; 10] mA
Important	[3 ; 4] J	[50 ; 75] N	[51 ; 70] °C		[80 ; 120] dB	[2000 ; 10000] cd/m^2	[3 ; 8] Gy	[10 ; 25] mA
Very important	[4 ; ++] J	[75 ; ++] N	[70 ; ++] °C		[120 ; ++] dB	[10000 ; ++] cd/m^2	[8 ; ++] Gy	[25 ; 2000] mA

Appendix 4: SMED method and case study results

SMED method:



*External activities are performed when the equipment is in production

Case study results

Parameters	Initial value	Final value	Improvement
Machine adjustment fastest reference	35 min	5 min	86%
Machine adjustment slowest reference	50 min	15 min	70%
Total welding time (added value)	3,15 min	3,9 min	25%
Manpower	2,5 workers	2 workers	20%

Juan Camilo GOMEZ ECHEVERRI

Cadre méthodologique pour la conception et modélisation des systèmes de production – Vers une intégration des exigences sécurité des opérateurs

Résumé

Depuis de nombreuses années, l'utilisation de machines en industrie est règlementée pour respecter des normes de sécurité et protéger les utilisateurs. Il s'agit tout autant de mesures de sécurité que de mesures d'ergonomie, l'objectif étant de protéger les travailleurs à long terme comme à court terme. Mais actuellement, de trop nombreux accidents du travail ou problèmes d'ergonomie sont observés sur les postes de travail. Dans ce contexte, l'objectif de cette thèse est de proposer un cadre de conception générique permettant de concevoir des systèmes de production complexes et multi-technologiques pour répondre à l'ensemble des objectifs de conception et de sécurité pour les opérateurs. Les résultats présentés dans ce manuscrit sont le produit de la confrontation entre les approches de conception existantes dans la littérature et les conditions réelles de conception d'un système de production au sein d'une PME. Le cadre général de conception s'appuie sur des concepts de différentes approches (conception basé sur le projet, sur le produit ou sur les activités du concepteur) agrégés dans un seul model pour simplifier l'intégration de la sécurité des opérateurs ou d'autres exigences dans le processus de conception. La modélisation proposée du system à concevoir est développé à partir d'une approche énergétique qui apporte au même temps toutes les informations nécessaires pour le développement du processus de conception et l'analyse de la sécurité des opérateurs. Cette modélisation prendre en compte le comportement, la structure et les flux d'énergie du système pour développer une solution adaptée aux besoins du client et qui réponds aux exigences industriels. La méthode proposée a été mis en application pour validation dans un cas d'étude d'un ilot de soudage d'une entreprise de la région dans le cadre de la Chaire industrielle Arts et Métiers et ses résultats sont présentés dans le document.

Mots clés : conception, systèmes de production, modélisation des systèmes, intégration de la sécurité

Résumé en anglais

For many years, the use of machines in industry has been regulated to comply with safety standards and to protect users. These are both safety and ergonomic measures, the objective being to protect workers in the long term as well as in the short term. However, there are currently too many occupational accidents or ergonomic problems at workstations. In this context, the objective of this thesis is to propose a generic design framework allowing to design complex and multi-technological production systems in order to meet all the design and safety objectives for the workers. The results presented in this manuscript are the product of the confrontation between existing design approaches in the literature and the real design conditions of a production system within an SME. The general design framework is based on concepts from different approaches (project-based design, product-based design or activity-based design) aggregated in a single model to simplify the integration of operator safety or other requirements in the design process. The proposed modeling of the system to be designed is developed from an energetic approach that brings at the same time all the necessary information for the development of the design process and the analysis of the safety of the operators. This modeling takes into account the behavior, structure and energy flows of the system to develop a solution tailored to the needs of the customer and that meets the industrial requirements. The proposed method has been applied for validation in a case study of a welding workstation of a company in the region within the framework of the Arts et Métiers Industrial Chair and its results are presented in the document.

Keywords: design framework, production systems, systems modeling, safety integration