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Contribution à la Conception et Conduite des Systèmes d'Information dans un contexte d'Usine du Futur par une Approche basée Co-Evolution

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A Jaime, à Cointa, à Anastasia et

à l’Etoile de ma vie

« Des pieds, pourquoi en voudrais-je,
si j’ai des ailes pour voler ».
Frida Kahlo

« Chaque voyageur parfait
crée toujours le pays où il se rend ».
Nikos Kazantzaki

« Si le cœur de l'homme ne déborde pas d'amour
ou de colère,
rien ne peut se faire en ce monde ».
Nikos Kazantzaki

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Résumé étendu en Français :
Contribution à la conception et conduite des Systèmes d'Information dans un contexte d'Usine du Futur par une approche basée Co-Evolution.

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Dans le contexte actuel, le système d'information (SI) est la pierre angulaire des organisations modernes, notamment pour les industries manufacturières. Un des challenges est d'intégrer les SI au système de production pour lequel il existe différents paradigmes de performance tels qu'Usine du Futur (Factory of the Future FoF), Industry 4.0 (I4.0) ou encore Smart Factory (SF). La transformation de l'outil industriel par l'intermédiaire de ces nouveaux paradigmes est au cœur des préoccupations actuelles des industriels. En France, elle est considérée parmi les 34 plans de rénovation du secteur industriel (Alliance Usine du Future, 2015). En raison du lien direct entre le rôle stratégique du SI et la gestion opérationnelle de l'entreprise, il est indispensable aujourd'hui de pouvoir répondre aux questions de l'adaptation du SI dans ce nouveau contexte. Celles-ci nécessitent de définir le rôle du SI dans l'industrie du futur, les liens existant entre eux ainsi que la gestion de leurs interactions dans un contexte en évolution constante.

L'objectif de cette thèse est de proposer une approche pour aider à la transformation des entreprises en utilisant une analyse de l'AS-IS pour définir la situation à atteindre TO-BE en prenant en compte la situation souhaitée AS-WISHED et les contraintes de ressources. Pour ce faire, la thèse est structurée de la manière suivante (voir Figure 1). Après l'état de l'art Chapitre 2, la contribution est structurée en trois parties : le modèle de co-évolution (présenté Chapitre 3), l'analyse des liens entre domaines (Chapitre 4), la démarche de co-évolution proposée (Chapitre 5). Une illustration industrielle illustre la contribution dans le Chapitre 5.

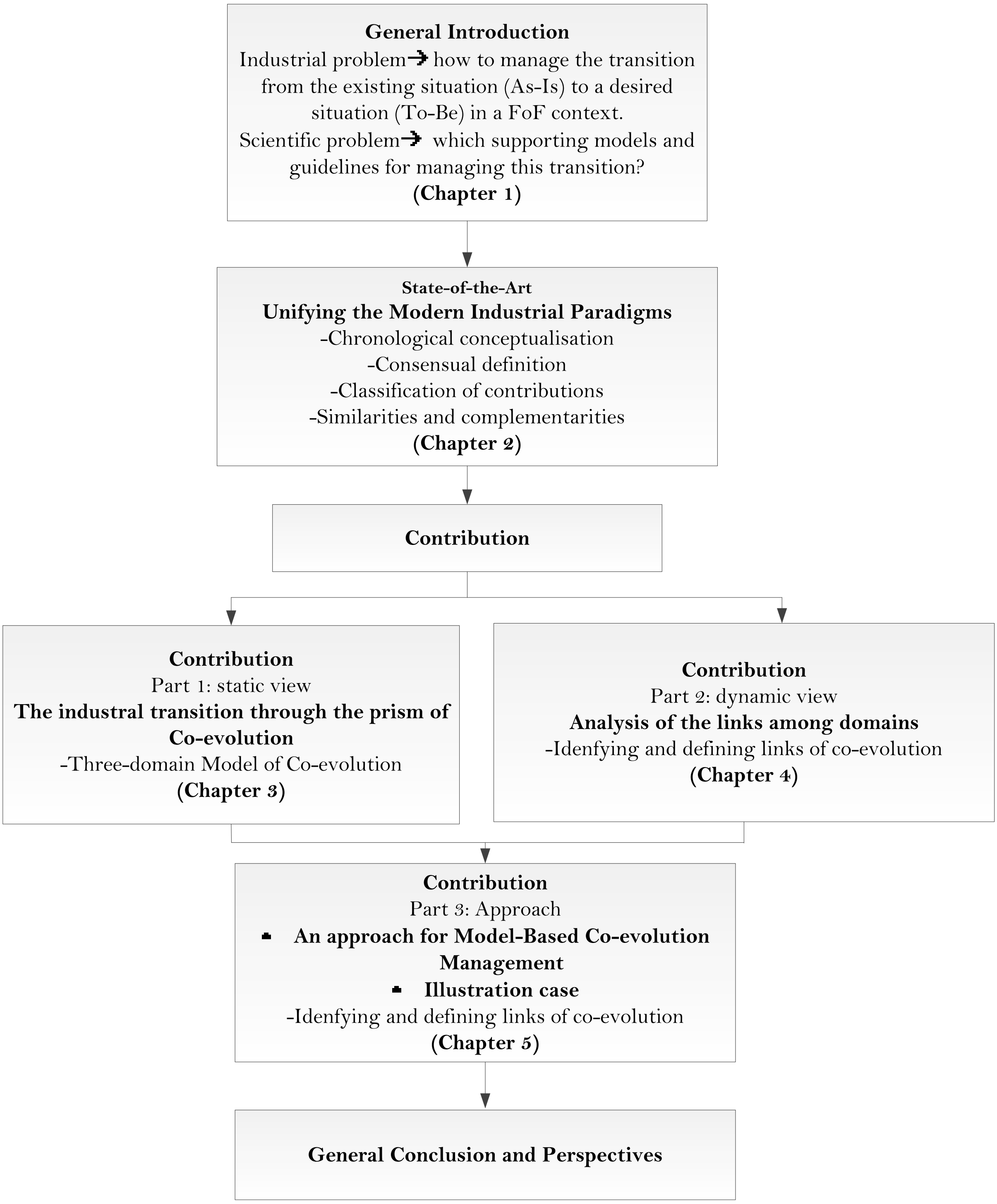

Figure 1 : Structure de la thèse.

Dans le Chapitre 2, nous partons de l'analyse de ces paradigmes afin de mettre en évidence leurs similarités et complémentarités. Pour ce faire, la revue de la littérature menées base sur le cadre de (vom Brocke *et al.*, 2009) nous a permis de caractériser chaque paradigme en mettant en évidence leur caractéristiques fondamentales. Ainsi, seule FoF n'a pas de définition unique puisque depuis les années 80 date où apparaît ce paradigme l'usine du futur évolue en fonction des innovations technologiques. Cependant, quoi il en soit la FoF est toujours l'intégration de divers développements technologiques pour aboutir à une production plus agile et flexible, au sein de laquelle l'homme doit co-évoluer. Le concept de SF est plus récent puisqu'il apparaît en 2006 dans le but de rendre plus intelligent l'atelier de production. Dans ce cas, l'usine est conçue pour rendre accessibles à tout moment et en temps réel les informations du contexte pour aider les machines et l'homme dans leurs tâches (Lucke *et al.*, 2008a). L'industrie 4.0, pour sa part, est née en 2011, d'une initiative allemande qui définit comme axe principal l'implantation des systèmes cyber physiques (Drath *et al.*, 2014).

L'analyse des similarités est synthétisée sur la Figure 2.

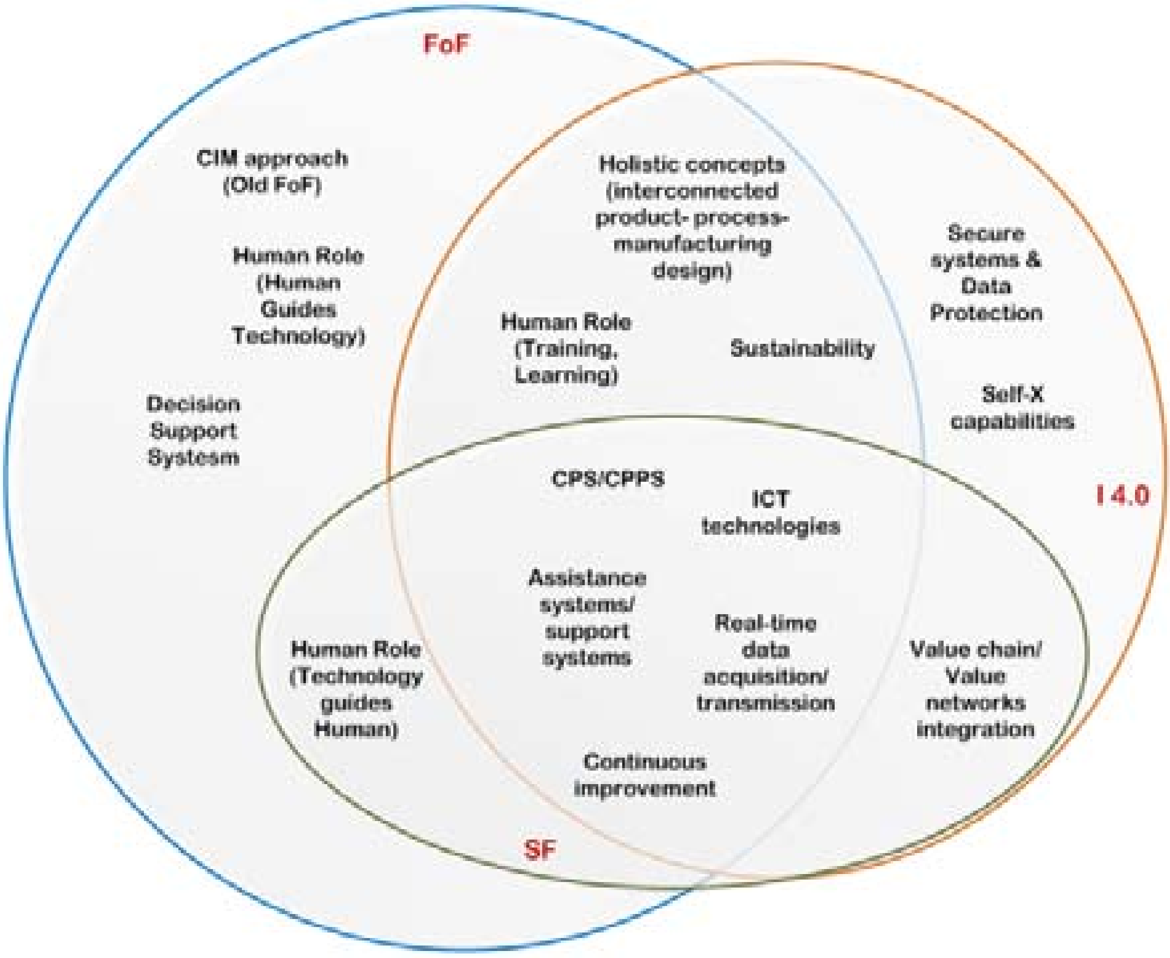

Figure 2. Similarité des caractéristiques FoF, SF et I 4.0.

Dans le Chapitre 3, nous retenons le modèle de coévolution proposé par Tolio *et al.* (2010). Ce cadre développé pour comprendre le problème des évolutions subis par le produit, les processus de production et le système de production au cours de temps et les impacts mutuels auxquels ils doivent s'adapter à l'aide des choix stratégiques est un premier pas pour comprendre la place du SI dans un contexte FoF. Cependant, il reste très macroscopique et ne permet pas de représenter finement les éléments en interaction ni comment gérer ces interactions.

Ainsi, sur la base des travaux de Tolio et al. (2010) nous proposons un nouveau modèle de co-évolution Produit/Production/Système d'information qui comporte (voir Figure 3) :

- 3 domaines : le produit (product), la production (manufacturing) et le système d'information (SI);
- Chaque domaine comporte deux niveaux : le niveau externe (external) et le niveau interne (internal) permettant de distinguer le positionnement externe (stratégique) dans ces domaines du positionnement interne c'est-à-dire l'organisation et les technologies choisies;
- Chaque sous-domaine est représenté par trois composants permettant, entre autres, de mettre en avant le rôle de l'homme par la définition des compétences nécessaires.

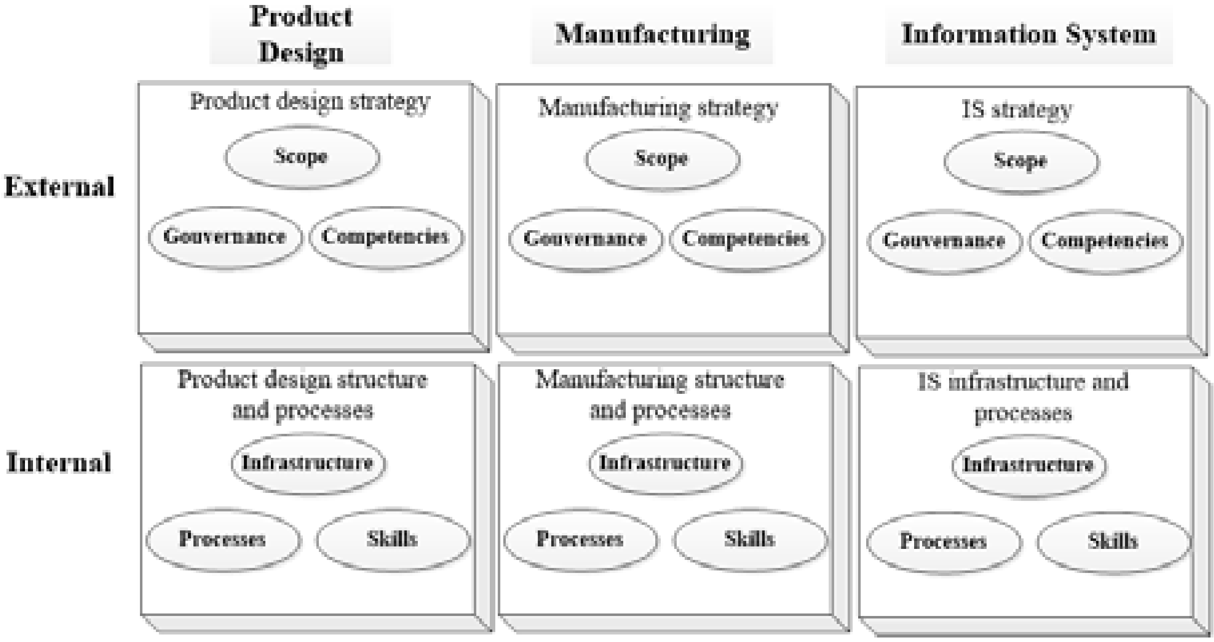

Figure 3. Modèle de co-évolution Produit/Production/SI

Pour pouvoir gérer la co-évolution entre ces trois domaines, nous proposons une approche basée modèle ainsi nous associons à chaque composant du niveau interne les construits de modélisation nécessaire en exploitant la norme ISO 19440 (cf. (ISO 19440, 2007)).

		Co-evolution Model Components at Internal level								
		Product Design			Manufacturing			IS		
	Modelling Constructs ISO19440	Design Structure	Design Processes	Skills	Infrastructure	Manufacturing & support Processes	Skills	Architecture	Processes	Skills
Function View	Domain		x			x			x	
	Business Processes		x			x			x	
	Enterprise Activity		x			x			x	
	Event		x			x			x	
Information View	Enterprise Object		x			x		x		
	Object view		x			x		x		
	Product		x			x				
	Order		x			x				
Resource View	Resource			x	x		x	x		x
	Functional Entity			x	x		x	x		x
	Capability				x			x		
Organisational View	Organisational Unit	x		x	x		x			x
	Organisational Cell	x								
	Decision Centre									

Tableau 1. Mapping entre les construits de modélisation de la norme ISO 19440 et les composants internes du modèle de co-évolution Produit/Production/SI

Dans le Chapitre 4, nous caractérisons les liens de co-évolution existant entre les différents sous-domaine du modèle de co-évolution proposé. Ainsi, nous identifions deux types de lien par analogie avec le SAM (Strategic Alignment Model) (Henderson *et al.*, 1993) à savoir :

- Le fit liant les niveaux externes et internes d'un même domaine. Il s'agit d'un strategic fit lorsque le lien va du niveau externe vers le niveau interne et d'un reverse strategic fit dans l'autre sens.

- L’intégration fonctionnelle qui lie des sous-domaines différents d’un même niveau. L’intégration est stratégique lorsqu’elle prend place au niveau externe et opérationnelle lorsqu’elle prend place au niveau interne.

Ces liens sont synthétisés sur la Figure 4.

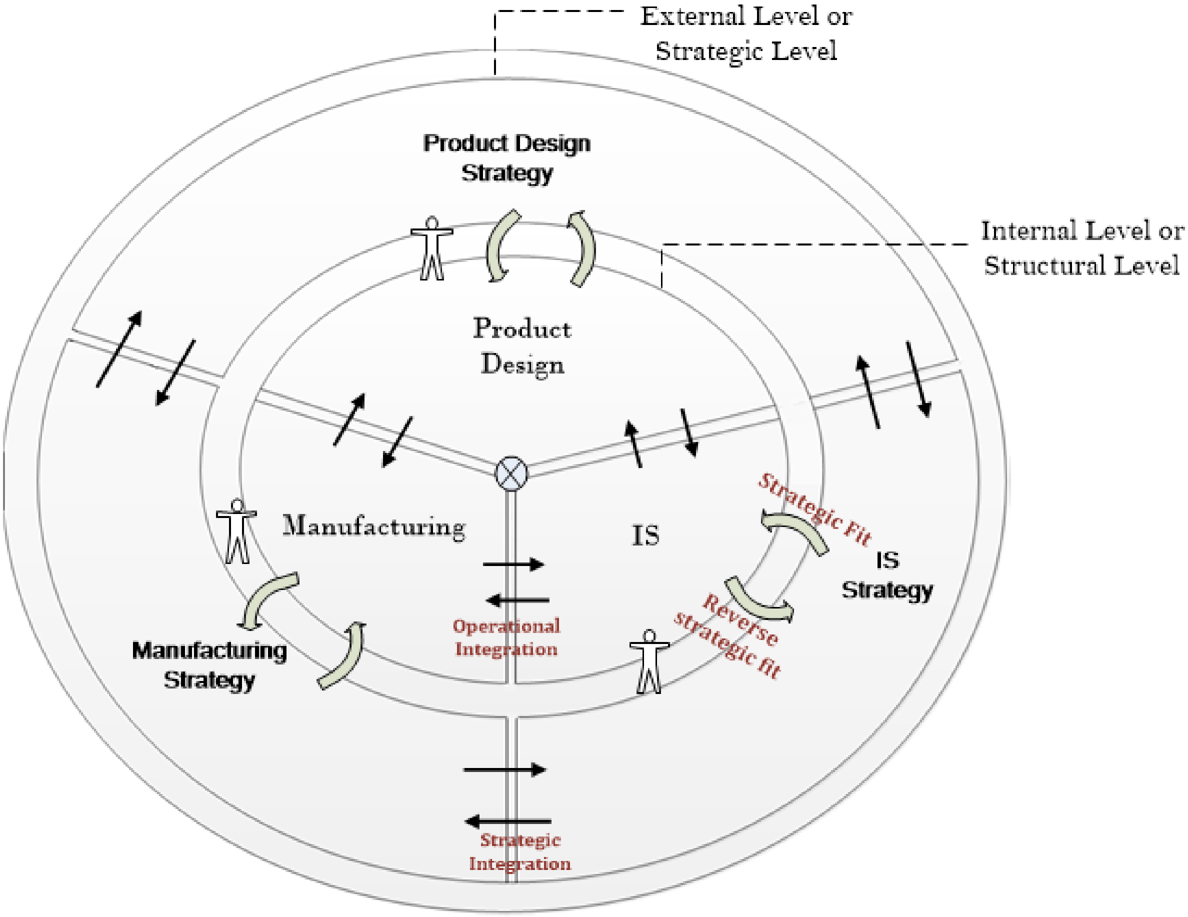

Figure 4. Liens entre sous-domaines dans le modèle de co-évolution.

Dans le Chapitre 5, nous proposons une démarche d’exploitation du modèle de co-évolution proposé et des liens entrant en jeu dans co-évolution. Cette démarche comporte 3 phases :

- L’instanciation des modèles AS-IS et AS-WISHED,
- L’identification du sous-domaine le plus impacté,
- L’instanciation du modèle TO-BE.

Cette démarche est synthétisée sur la Figure 5.

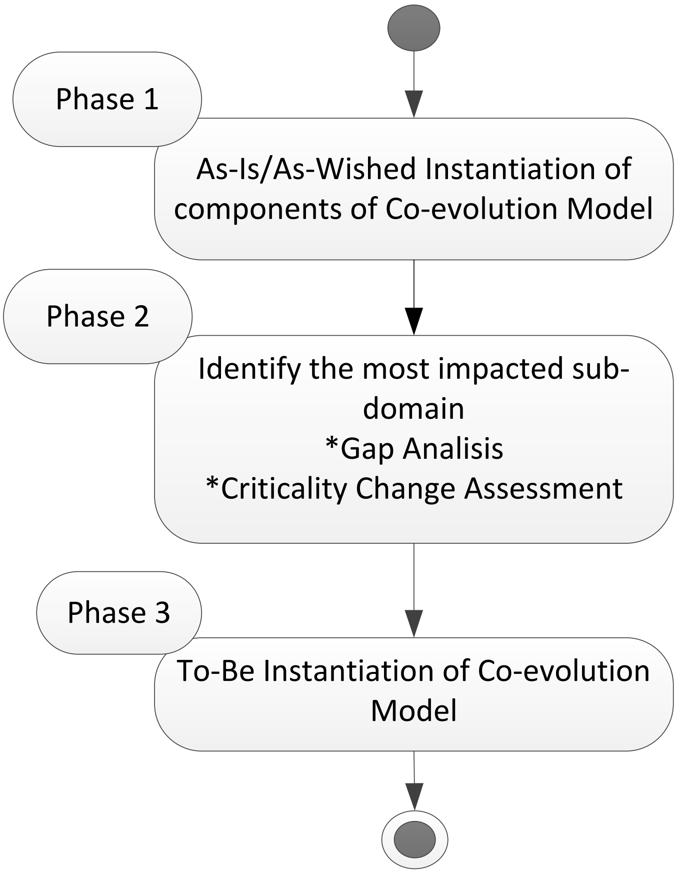

Figure 5. Représentation synthétique de l'approche de co-évolution.

L'étape cruciale est l'identification du sous-domaine le plus impacté. Cette étape est détaillée sur la Figure 6.

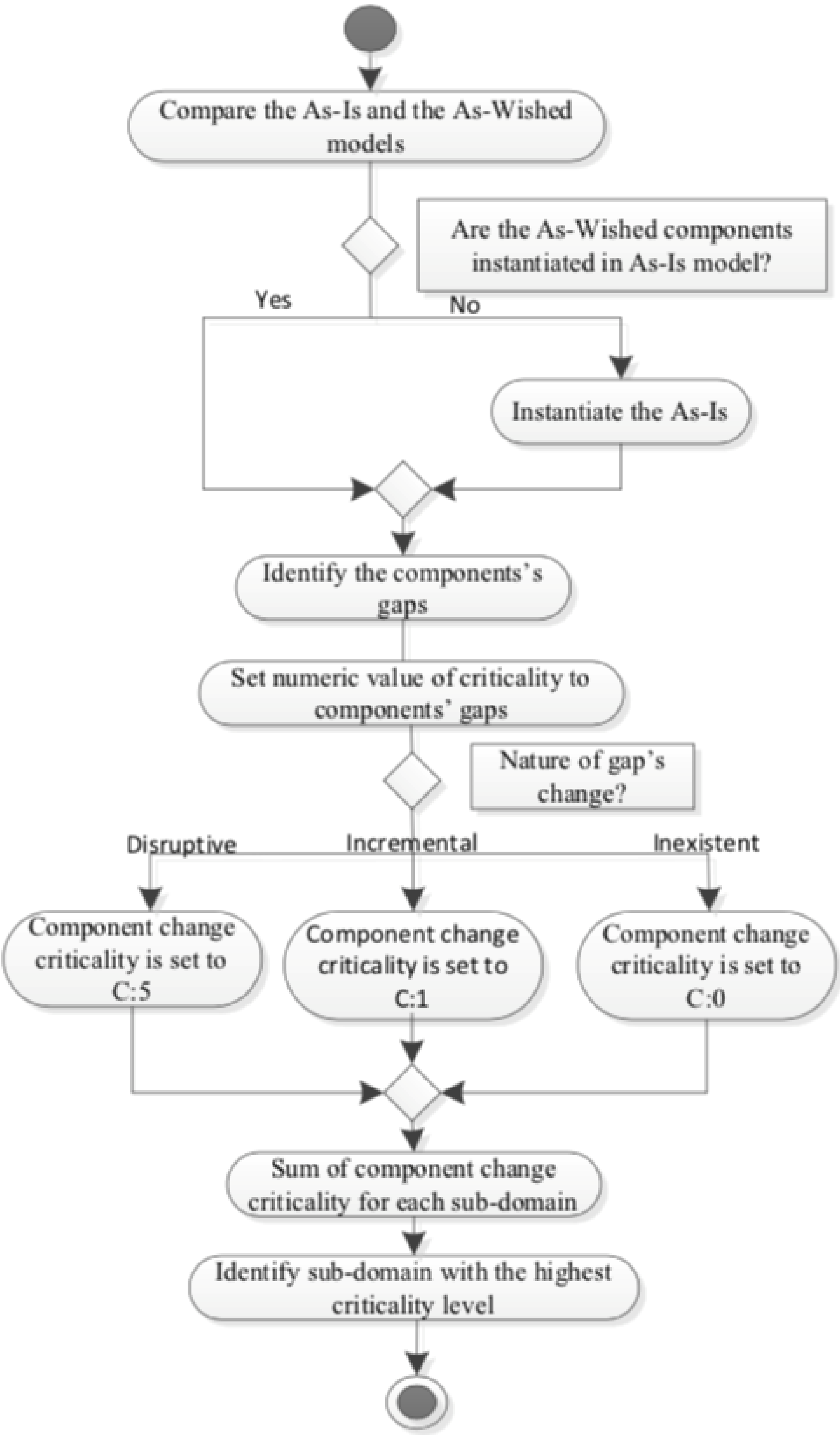

Figure 6. Identification du sous-domaine le plus impacté.

Cette démarche est illustrée sur un cas industriel sur lequel l'accent est mis sur la dimension produit.

En conclusion générale, les contributions sont synthétisées et les perspectives suivantes sont listées:

- Évaluation de l'efficience de l'approche proposée sur une application industrielle.
- Développement d'un logiciel de support à l'approche proposée (aide à l'instanciation des modèles, analyse des alternatives, …).

Couplage avec une aide au choix de solutions technologiques intégrant l'évaluation de leur soutenabilité.

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Chapter 1. General Introduction

1 Research Context and Problem Statement

The evolution of production methods in the manufacturing industry underpinned by the breakthrough technologies of Information and Communication (ICT) has opened a wide range of opportunities to produce in a more intelligent but also in a more sustainable way. Several conceptualizations have emerged to characterize these ongoing evolutions such as the 'Factory of the Future' (FoF), the 'Smart Factory' (SF) or the 'Industry 4.0' (I4.0). Despite the variety of concepts, all these new paradigms of performance converge upon a common global strategy: the transformation towards the next generation of industries.

For instance, the 'Factory of the Future' vision takes part as one of the 34 plans for the renewal of French industrial sector (Alliance Usine du Future, 2015). The European Commission launched the Horizon 2020 framework program in 2014 aiming to increase its stake in manufacturing competitiveness through the 'Factories of the Future' initiative (Filos, 2015). Other related 'FoF' initiatives, in the global context, are the so-called 'Future of Manufacturing' by the United Kingdom (UK) government, the 'Made in China 2025 strategy' from the Chinese government, or among the industrial plans perspectives, the Internet Consortium (IIC) founded in 2014 (Liao Y. X. *et al.*, 2017). These initiatives underpin the coordinated efforts focused on guiding the ever-evolving manufacturing industries in the long-term direction.

Beyond technologies and equipment, these evolutions have major implications on the business processes, labour and organization models. For these new organizations, the Information System (IS) remains the cornerstone for the creation of competitive advantages within an environment particularly evolutive and competitive.

In order to follow the modernization of production tools, the close relationship between the organization and the IS supporting the enterprise business has to be considered. Any organizational change has an impact on the evolution of IS. The higher agility and flexibility provided by FoF, SF or I4.0 implies a flexible IS that fits to that context. This requires industrials to manage the transition from the particular existing state (AS-IS) to the FoF-oriented desired situation (TO-BE) handling the complex interrelations within an organization.

As a consequence, it is crucial to provide to companies management tools enabling to deal with the related transformation from an holistic point of view.

The present research work aims to provide a contribution allowing to support the transformation of manufacturing companies from a point of time in the present (AS-IS) towards a point of time in the future (TO-BE) allowing to operate in a context that fulfils the evolutions imposed by the modern paradigms of performance. To reach this target, the underlying problems that we aim to solve can be formulated as follows:

- What changes are implied by the industrial paradigms stated to address the vision of future factories?
- What are the main challenges according to them?
- What elements are needed in order to design factories-of-the-future and the related IS?

Supported by the knowledge from addressing the previous questions, our research work focuses on the following key research question:

- How to address the transition from one specific situation (AS-IS) to a new one (TO-BE) in a context where Factory of the Future takes place?

Thanks to the state of the art that we have carried out on the main industrial performance paradigms FoF, SF and I4.0, we propose to work out our contribution on the co-evolution model proposed in (Tolio et al., 2010). On the basis of the co-evolution perspective, we make the hypothesis that we can handle the continuous adaptation of the IS, the manufacturing and the product design over the time necessary for a successful transformation of the industries. Our contribution exploits the original model co-evolution model of (Tolio et al., 2010) by proposing a more robust and complete model of co-evolution to be fully leveraged for the transition of the manufacturing companies.

To complete the model, we integrate missing elements such as the strategic dimension necessary to consider top-level decisions. We also integrate the IS and the human workforce role, which are crucial to reach our objective of consistent transformation. We propose to structure our model in the same way as the Strategic Alignment Model of (Henderson et al., 1993) which has broad acceptance among academic scholars. We provide formalization methods enabling the effective use of the proposed co-evolutions model. So, we propose to map the modelling language constructs defined in the ISO 19440 (2007) to the internal components of the co-evolution model representing the operational level and in turn propose corresponding relevant languages. The model completion also concerns the description of the co-evolution links.

Finally, we propose to exploit the co-evolution model through a co-evolution management approach. The proposed approach consists in a set of steps that includes the instantiation of the co-evolution model at different time periods of the evolution axis. The temporal dimension allows to distinguish and represent different states including the present situation (AS-IS), the future potential evolution scenario that the company wants to reach (AS-WISHED) and the feasible state that is derived considering organisational requirements (TO-BE). Moreover, the approach is based on the assessment of the change criticality and rules to manage the co-evolution links. As a result, our approach allows to manage the co-evolution of the product design, manufacturing and IS domains over time. Our approach integrates the feasibility and co-evolution constraints as well as stakeholder's needs in order to derive the feasible evolution scenario (TO-BE). As a result, a co-evolution path is defined which reflects the control of the synergic impacts among the involved organizational domains. The proposed co-evolution management approach is illustrated considering an industrial scenario linked to the objectives of the 'FoF' context.

2 The Structure of this Manuscript

This dissertation is structured as a collection of essays, all of which have been, or are about to be, submitted to international conferences or peer-reviewed journals. Although we have reworked the papers to reduce redundancy as much as possible, even is a certain level of repetition is bound to appear. We ask for the reader's understanding on this point. To ease the reading, all the references have been gathered at the end of the dissertation. The scientific papers that we carry out are structured in five chapters allowing, first, to understand the scientific context in which this work takes place, and second, to present the contribution proposed which can be divided into two main parts: the definition of the static and dynamic views of the model of co-evolution and the complete approach to exploit the model for the management of co-evolution. Finally, the use of the proposed model-based co-evolution approach is illustrated on a real case.

- **Chapter 2: Unifying the Modern Industrial Paradigms: Factory of the Future, Smart Factory and Industry 4.0: A Literature Review**

The first chapter of this thesis concerns the state-of-the art article will be submitted for publication in IJPR (International Journal of Production Research) this summer. Previously two articles one dedicated to the concept of the Factory of the Future and the other one to Smart Factory have been presented at the IFAC World Congress. In this chapter, we aim to provide simultaneously a synthesis of the modern paradigms of industrial performance FoF, SF and I4.0 that are changing the manufacturing landscape. We analyse the key concepts and their underlying approaches and contributions by applying an iterative procedure based on the literature review process of Brook. Based on the performed state-of-the art, we have emphasized the role of the Information System (IS) and the role of the human workforce in relation to these paradigms.

- **Chapter 3. Factory of the Future: The Industrial Transition through the prism of Co-evolution**

This chapter concerns an article accepted by the IEEE International conference SMC 2019 (System, Man and Cybernetics). We explain in the first instance in this chapter the work of Tolio et al. (2010) which presents a co-evolution model taking into account three entities. We detail the contributions and the shortcomings of this model. Based on this work, we introduce a new co-evolution model. We define domains, bundling the entities and integrating the Information System (IS), the strategic dimension, and the role of human workforce. As such, this first part of the contribution represents the static view of the model.

- **Chapter 4. Analysis of the Links existing among the Domains of the Co-evolution Model**

1. The chapter 4 and 5 will be part of a final article to present our work and will be submitted in the next weeks soon. In this chapter 4, we address the dynamic view of our co-evolution model in terms of the potential interactions or links that relate the domains. We identify and describe two main types of bi-directional links: 1) the Strategic fit and reverse Strategic fit and 2) the Functional integration which includes the Strategic integration and the Operational integration. We justify the potential relationship of each type of link by exemplifying them considering the three domains represented: Product design, Manufacturing and IS domains. As a result, 9 potential bi-directional links are tackled. As such, this is the second part of the contribution which represents the dynamic view of the proposed model in terms of the co-evolution links that have to be dealt with over time.

- **Chapter 5. An Approach for Model-based Co-evolution Management**

In this chapter, we propose the approach that exploits the proposed co-evolution model (static and dynamic view) in order to provide a tool for the management of co-evolution. This approach is then illustrated through a real industrial case.

- **Chapter 6: General Conclusion and Perspectives**

The dissertation ends with a classical conclusion and research perspectives chapter.

The Fig represents the general structure of this thesis:

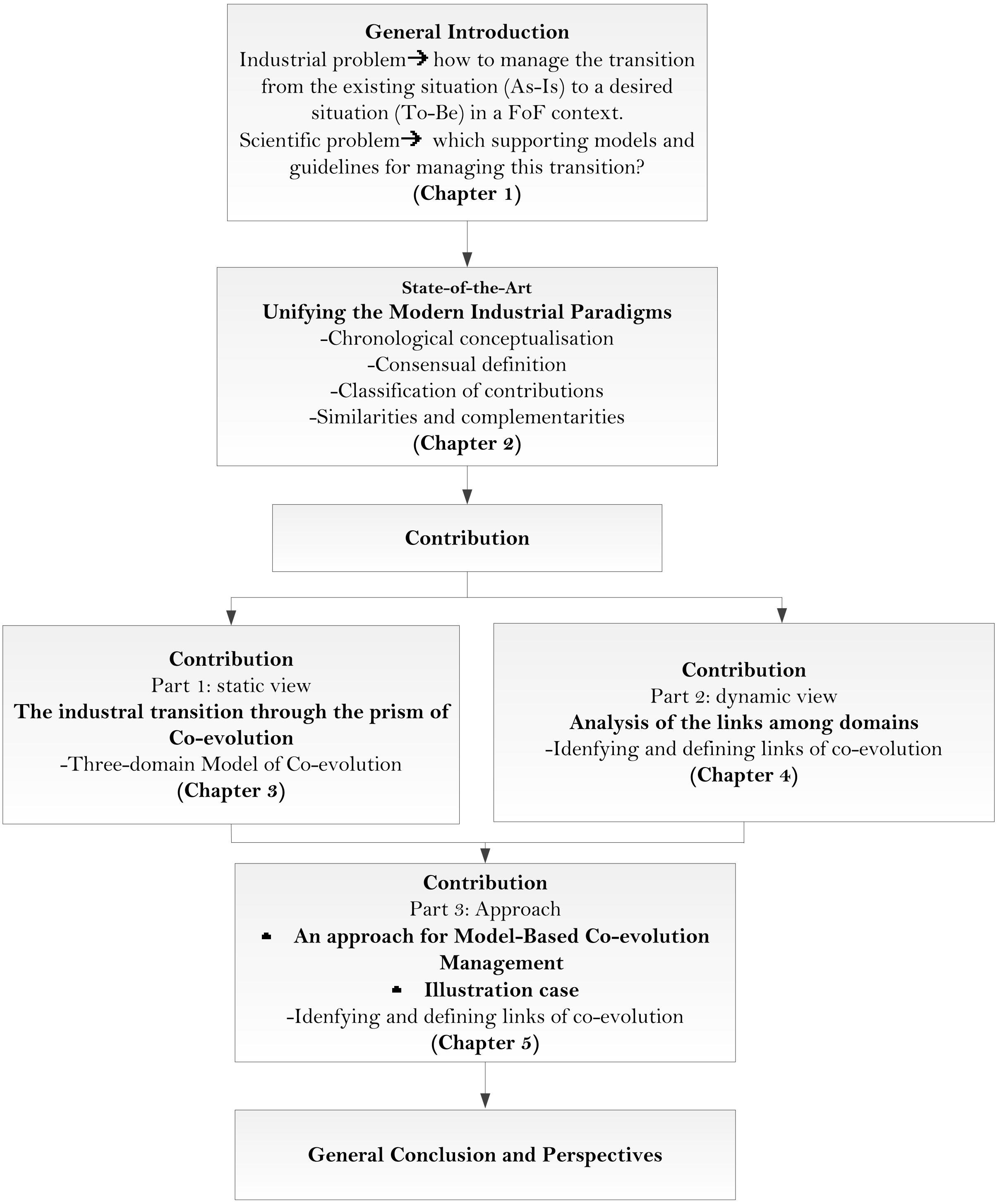


Figure 1. Structure of the PhD dissertation

Chapter 2.

Unifying the Modern Industrial Paradigms: Factory of the Future, Smart Factory and Industry 4.0: A Literature Review

1 Introduction

With the growing need to face changing product requirements and become adaptive to economical, socio-political and technological changes, manufacturers are seeking new ways to achieve challenging performance levels (Tolio et al., 2010). The future of manufacturing implies the development of: re-usable, flexible, modular, intelligent, digital, virtual, affordable, easy-to-adapt, easy-to-operate, easy-to-maintain and highly reliable 'factories of the future' (Tepes *et al.*, 2015). Thus, factories have to adapt to ever new trends and paradigms in manufacturing to stay competitive (Herrmann *et al.*, 2014). Another crucial development is related with the use of Information and Communication Technologies (ICT) as enabling technologies (Tepes et al., 2015). Revisiting the literature from the outset of the computerized factory led to identify the search for higher flexibility under the term of 'the Factory of the Future' (FoF) as observed in the eighties (Meredith, 1987). According to (Lucke et al., 2008a) a next step of evolution is handled under the so-called 'Smart Factory' (SF) concept. Last, but not least, the term 'Industry 4.0' (I4.0) is introduced by the German government in 2011 (Lasi *et al.*, 2014), named with the eponym of the so-called fourth industrial revolution.

In this paper, we address simultaneously these main industrial paradigms: FoF, SF and I4.0. Although they enable, in principle, the evolution of a given manufacturing system, a critical issue is how industrials choose among these concepts and how they find the right path towards their implementation. Prior contributions generally focus on only one of these concepts. They deal with future research directions of some of these paradigms, such as in the review proposal of SF by (Strozzi *et al.* (2017) as well as the review conducted by (Liao Yongxin *et al.*, 2017) on the topic of I4.0. The major objective in our literature review is, in a complementary fashion, to make a point on the underlying objectives of FoF, SF and I4.0 as well as on the corresponding approaches for concrete design and implementation of them in order to pinpoint their complementarities. The literature review we perform is based on the iterative bibliographical analysis process from (vom Brocke et al., 2009) which allows us to structure our research work.

The review paper is structured as follows. In Section 2 we describe the iterative process underpinning our literature review. Sections 3, 4 and 5 correspond to the reviews performed for the concepts of FoF, SF and I4.0. Each section comprises the main definitions of the considered concept as well as our own conceptualisation derived from them enabling in turn to clarify the goals and implications behind each of them. Then, we give an overview and analyse the tools, methods and approaches enabling to design and implement a given concept. Section 6 focuses on the similarities and common characteristics within each concept and how they can be combined and contribute to each other. Future research directions and conclusions are proposed in Section 7.

2 Research Methodology and Results

To structure the literature review we perform, we found several works focusing on meaningful recommendations. For example, Kitchenham *et al.* (2007) provide guidelines for performing a systematic literature review in Software Engineering. They suggest a three-phased approach: i) Planning the review, ii) Conducting the review and iii) Reporting the review. As well, (vom Brocke et al., 2009) propose an iterative circular process to carry out a literature review. It integrates 5 main steps (see Figure 2): i) Definition of review scope, ii) Conceptualisation of topic, iii) Literature search, iv) Literature analysis and synthesis and v) Research agenda. This process is interesting because of its iterative nature and because it details the planning and reporting review steps proposed in Kitchenham et al. (2007). Indeed, the review scope has to be defined and the topic conceptualised before performing the literature review as such. Moreover, the result of the literature review is a research agenda, which is why our work is based on this process.

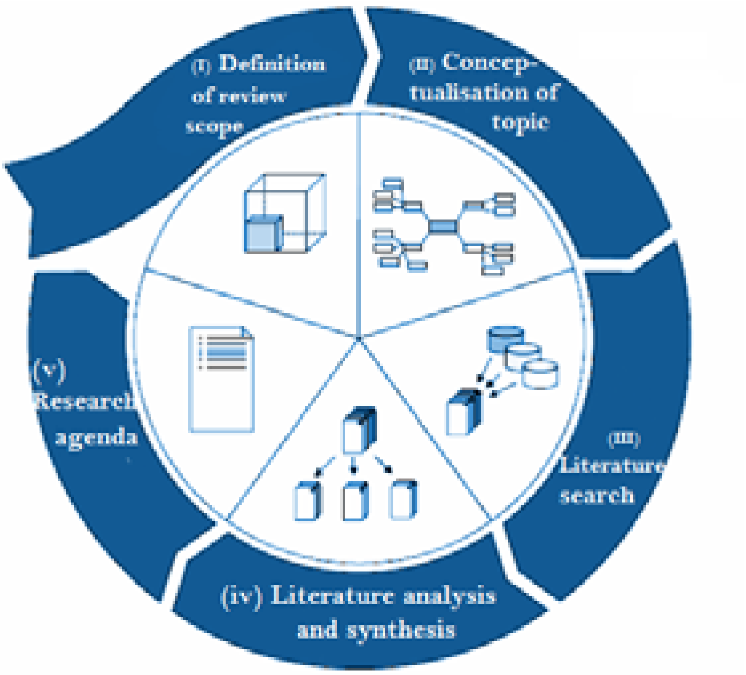


Figure 2. Iterative process for literature review (vom Brocke et al., 2009)

The application of this process to our review is as follows:

Definition of review scope: As we seek to delineate clearly the concepts of the FoF, SF and I4.0 and their complementarities, we focus on the research works published over each one of these topics solely or in a combined manner.

Conceptualisation of topic: To accomplish our review scope, we perform main and combined queries into the ISI Web of Science database as shown in Table 1.

Literature Search: When performing the queries, we focus on the following areas of research: 'Engineering', 'Computer Science', 'Business Economics', and 'Operations Research Management'. The type of documents that we will retrieve is set up as: 'Articles', 'Conference Proceedings' (Conf. P) and 'Reviews'.

Queries performed and Results (ISI Web of Science database)				
Main Queries	Retrieved papers			
	Articles	Conf. P	Reviews	Total
Factor* of the Future	94	76	3	165
Smart Factor*	41	129	4	174
Industr*4.0	142	431	14	573
Combined Queries				
Factor* of the Future AND Smart Factor*	2	5	1	8
Smart Factor* AND Industr* 4.0	13	43	4	62
Factor* of the Future AND Industr* 4.0	4	6	1	14
Factor* of the Future AND Smart Factor* AND Industr* 4.0	2	2	1	5

Table 1. Retrieved papers from the queries executed.

Literature analysis and synthesis: We analyse the papers for each concept in a chronological sequence according to the origin of concepts. Thus, we begin with the FoF concept which emerges in the eighties, then we deal with the SF concept dating from 2007 and we finish with the I4.0 that emerges in 2011. We have applied the iterative process of (vom Brocke et al., 2009) several times for each concept. First, the iterative process is applied to work out a consensual definition of each concept. Then, a second iteration is applied for the analysis of the tools, methods and approaches proposed and embrace two internal iterations. The first one concerns the analysis of the abstracts in order to define the type of contribution. The type contribution enables to detail the scope of the contribution and its kind. For the scope, it can be either engineering that is to say contributing to design a FoF, SF or I4.0 oriented manufacturing system, implementation that is to say dedicated to implement a FoF, SF or I4.0 manufacturing system or proposing a review. For the kind of the contribution, we define if it is technological based or methodological based. The second internal iteration is applied to the full text version in order to analyse the nature of contribution that is to say how it enables to meet the underlying objectives of each concept. These objectives are deduced from the definition analysis.

Research agenda: Our study examines the definitions of the FoF, SF and I4.0 concepts and highlights corresponding design and implementation approaches as well as their specificities and complementarities.

3 Factory of the Future Literature Analysis

3.1 Factory of the Future Definitions

One of the first reference to the term FoF dates from 1987 in the keynote speech of Welber A. (1987) that describes a FoF as "*a very large scale intelligent machine that operates with a highly integrated and well-organized base of knowledge [which] must be flexible with regard to changes in demand, technology, economic conditions, and competitive*". During this period, it is acknowledged that a factory of the future should focus on integrating the manufacturing process through the integration of the various manufacturing and information subsystems (Ford *et al.*, 1985) given rise to the CIM (Computer Integrated Manufacturing) research stream. In (Meredith, 1987) the technologies to be integrated into a FoF encompass engineering techniques, manufacturing techniques and business techniques and these should have both internal but also external benefits enabling a given company to stay competitive.

In the nineties, the view of FoF evolves towards a fully automated factory to produce personalized products resulting in a combination of organizational change and intelligent use of information or knowledge technologies as underlined in (Jackson *et al.*, 1992).

As the 21th century begins, the evolving FoF brings forward more flexible, agile and modular production systems that become intelligent with high added value. This is evidenced by researchers such as Simsek *et al.* (2004) who argue that FoF "*is dependent on the development of autonomous, agile, scalable, modular and reliable tools controlling all the processes throughout the production chain in an intelligent manner*". Later Bathelt *et al.* (2010) describe the FoF as "a *long-term shift from a cost-based competitive advantage to one based on high added value*" and Jufer *et al.* (2010) add that FoF is customer-oriented manufacturing producing and offering large number of products "*which are sustainable and of high value in the same time frame*".

More recently the sustainable feature of FoF becomes crucial as stated in Guerra-Zubiaga *et al.* (2016) where FoF is described as "*an evolving solution supporting sustainable manufacturing throughout the lifecycle of products and services*". In the same vein, the European Commission (2016) considers FoF as "*transformable, networked and learning factories, depending on several drivers such as high-performance, extreme customization, environmental-friendliness, superior efficiency of resources, eminent human potential and significant knowledge creation*" as cited in (Jardim-Goncalves *et al.*, 2017).

In a global view, FoF is defined in terms of its features enabling manufacturing companies to stay competitive. These evolve over time. In the 80's FoF is portrayed as CIM passing, in the early 90s, through the development of flexible manufacturing techniques and advanced automation technologies, but steadily in search of more flexibility. In a consensual view, FoF is seen as the highly integrated, organized and intelligent control of the production chain (Simsek et al., 2004 ; Welber A. , 1987) ensuring high added value and sustainable products and services (Bathelt et al., 2010 ; Jufer et al., 2010). As a result, the FoF is able to drive improved manufacturing features related to customization as well as the creation of relevant knowledge and human potential (European Commission, 2016).

3.2 Characterisation of Factory of the Future Research Works

We retrieve 165 papers initially from the query. We exclude 20 papers released from the combined queries that we analyse in further sections and 22 papers that were anonymous or without abstract and full version available. As a result, a total of 123 research papers were analysed as detailed in section 2.

Table 2 shows the paper distribution according to the type of contribution. A majority of papers (56%) deals with implementation. In both categories, the contributions are essentially methodological based.

Contribution Scope and Kind		**Number of papers**	**%**
Engineering		51	42%
	Methodological-based (ME)	44	86%
	Technological-based (TE)	7	14%
Implementation		68	56%
	Methodological-based (ME)	45	66%
	Technological-based (TE)	23	34%
Reviews		3	2%
Total		123	

Table 2. Distribution of the type of contribution for FoF literature analysis

For the analysis of the nature of the contributions, we set up the categories according to the definition analysis we made in section 3.1. This analysis shows that a FoF is an integrated factory in which the role of the human workforce is crucial. The way to make this integration evolves over time. Therefore, we propose three categories:

- The CIM approach that represents 22% of the papers analysed;
- Other integration approaches representing 51% of the papers analysed;
- The role of human work force representing 27% of the papers analysed.

Next section synthesizes the analysis of the papers according these three categories.

3.3 Factory of the Future Research Work Analysis and Synthesis

Within the CIM approach category, we group contributions dating from 1984 to 1998 that concern the earliest vision of the FoF. In a general picture, the papers of this category display mostly methodological-based contributions to manage computer-aided production techniques (CAD, CAM, Flexible Manufacturing System (FMS)) at the core of the FoF (Jelinek *et al.*, 1984 ; Mulder, 1990 ; Tie *et al.*, 1992). The engineering contributions focus mainly on the production models, generally flexible automation, to set up in a CIM context. For example, Rolstadas (1991) and Wortmann (1992) propose a model for "FoF Production Theory" consisting in a theoretical framework and a design framework enabling to make the link between design choices and performance indicators. For the implementation contributions, the focus is on the technological and enablers and barriers for CIM such as (Jelinek et al., 1984) who describe four major success features.

Within the category of Other Integration Approaches (from 1998 to 2017) there is a balanced distribution between engineering and implementation contributions. We identify three streams of integration, here named in decreasing importance: holistic factory, continuous improvement and sustainable production.

First, special focus is put on the design and implementation of FoF from a holistic perspective, including the manufacturing but also the product design functions of a given factory. For engineering such a factory, the concept of co-evolution of products, processes and production systems (P3S) of (Tolio et al., 2010) brings together a deep insight to understand how to manage this concurrent evolution, even if the co-evolution model proposed is too macroscopic to effectively guide the design of a given FoF. In a similar way, the formalism detailed in (Moghaddam *et al.*, 2017) enables the design of a collaborative FoF. For implementation, the works generally focus on interoperability. For example, Tchoffa *et al.* (2016) address networked collaborative product development based on evolving Product Lifecycle Manufacturing (PLM) standards. However, more research is required concerning the constraints and requirements to develop complying IS able to support such interconnected structures. Accordingly, the FoF should offer opportunities to interrelate the manufacturing processes among enterprises in order to effectively handle lifecycle management of the resources shared. The second aspect most addressed in this category concerns continuous improvement of the factory through various lines of action. From the engineering point of view, it mainly concerns the development of virtual manufacturing and digital twins like in (Grladinovic, 2001 ; Souza *et al.*, 2006). For implementation, either global performance measurement methods and tools are developed like in (Jufer et al., 2010 ; Pirani *et al.*, 2016) or use of ICT to improve specific elements of the production system are developed like in (Dhuieb *et al.*, 2013 ; Everett *et al.*, 2017 ; Fiaschetti *et al.*, 2015). Third, an emergent trend in FoF engineering and implementation is the focus on sustainable factories. In this sub-category the works mainly deal with waste and energy management in manufacturing. Concerning engineering, several works like (Cerdas *et al.*, 2015 ; Ding *et al.*, 2010 ; Herrmann et al., 2014) propose very coarse guidelines to set up a more sustainable factory. Concerning implementation, the focus is on renewable energy use and management like in (Espinosa *et al.*, 2012 ; May *et al.*, 2016) or on tools enabling this optimization like in (Belkadi *et al.*, 2015 ; Walmsley *et al.*, 2016).

The last category, the role of the human workforce emphasizes the evolving trend towards the human-centred FoF. Thus, the engineering works focus on models enabling to handle specific design aspects of human-centric workplaces where human is a key factor like in the work of Zamfirescu *et al.* (2014). The adaptive role of the workforce gain interest as stated in (May *et al.*, 2015 ; Romero *et al.*, 2015) aiming to cope with skills demands. Likewise, the implementation-driven methods mainly address the issue of skills gaps through teaching and training approaches as in (Chryssolouris *et al.*, 2016 ; Perini *et al.*, 2016). However academic training is more favoured than industrial learning. Also, the studies cover in most cases the human role at the manufacturing level and do not provide sufficient insight into the role of human at other levels of the enterprise.

In a nutshell, what FoF represents is mainly an evolutionary system forming a unified whole. For this, each sub-system has to be managed considering its interrelations with other entities in an increasingly networked-driven and constantly changing context.

4 Smart Factory Literature Analysis

4.1 Smart Factory Definitions

Throughout the literature review we perform, a large number of statements are found, loosely linked to the concrete meaning of the Smart Factory (SF) concept. In fact, most of them highlight components that may be integrated to SF or the benefits expected through its application. In this section, we present four concrete definitions we identified and that were proposed during the adoption and development period of the concept from 2008 to 2016.

First, Lucke *et al.* (2008c) propose a global definition of SF by stating that it is: '*a factory that context-aware assists people and machines in execution of their tasks*' and '*enables real-time collection, distribution, and anytime/anywhere access of manufacturing relevant information to enable an easy overview of location and condition of factory objects*'.

Later, (Rashid *et al.*, 2012) point out present the SF as a: '*context-sensitive environment that can handle turbulences in real-time production using decentralized information and communication structures for an optimum management of production process*'.

In addition, the elements that need to be connected inside the factory to become smart are highlighted by Han *et al.* (2016). Accordingly, SF is: *'a new kind of factory that gathers and processes the data from the whole manufacturing process by connecting all the machines, workers, products, and environment'*.

Similarly, higher interconnectedness is the main premise for SF as put forth in the definition given in (Turner *et al.*, 2016): *'a manufacturing plant that features network-connected smart machines, data repositories, and integrated sensing technologies to provide human-responsive context-aware production lines'*.

Finally, Wang J. P. *et al.* (2016) confine the SF to the specific integration of physical and digital components realized by Cyber-Physical Systems (CPS). As such, they define the SF as: *'a CPS that integrates physical objects with Information systems to implement flexible and agile production'*. In this case, the concept of SF is very restricted because it lies uniquely on a technology-based approach.

Importantly, the related term of "Smart Manufacturing" is accounted by some authors as a driving force for innovation and improvement of the manufacturing industry (Kang *et al.*, 2016 ; Waurzyniak, 2016a, b ; Weber, 2016). According to the NIST (National Institute of Standard and Technology), Smart Manufacturing is defined as: *'fully-integrated and collaborative manufacturing systems that respond in real time to meet the changing demands and conditions in the factory, supply networks and customers needs'* (NIST, 2014). This term promotes the use of technologies on the factory shop-floor to leverage the intelligence of the production systems as a specific aspect of the SF.

As mentioned, most definitions outline the information-driven feature and main components of the SF as in (Han et al., 2016 ; Rashid et al., 2012 ; Turner et al., 2016). They also refer to the general motivation behind SF development that is to say a better production management, through interconnectedness and context-aware production lines. Wang J. P. et al. (2016) address a narrower definition of SF based on a highly techno-centred approach. As a result, we believe that the definition of Lucke et al. (2008c) gives more precision to the term SF and its specific functionalities for the industry. Thereafter, we exploit this definition to support our literature review process.

4.2 Characterisation of Smart Factory Research Works

From the initial query, we retrieved a total amount of 174 research papers. We excluded 18 papers that are out-of-scope because they do not concern the SF development. Other reasons were the lack of the full version of the paper as well as duplicated content. The combined queries give us a total of 67 papers, which we take aside for specific analysis. Thus, we account a total of 89 eligible papers for our analysis of the SF concept.

The SF contributions are also classified according to the scope of contribution (engineering or implementation) and kind of contribution (methodological or technological based).

Moreover, each work is examined according to its ability to meet a set of requirements derived from the SF definition of (Lucke et al., 2008c). Indeed, designing a SF requires to define: (1) Which data to collect, (2) The kind of access to the data, (3) Which actors will have access to these data and (4) Which technologies will provide these functionalities. When implementing a

SF four functionalities are required: (1) Real-time data collection, (2) Real-time data distribution, (3) Real-time data access and (4) Assistance support.

Last but not least, for engineering, we also identify complementary approaches that highlight the integration, into the SF design, of specific concerns like safety in (Nicklas *et al.*, 2016). For these approaches, because of their specific focus, the analysis towards the underlying requirements derived from the SF definition is not made. From the 89 papers reviewed, 40% are engineering oriented, meaning that the major part of these publications is dedicated to the implementation of SF as we can see in Table 3.

Contribution Scope and kind of contribution		**Number of Papers**	**%**
Engineering		36	40%
	Methodological-based (ME)	11	31%
	Technological-based (TE)	25	69%
Implementation		53	60%
	Methodological-based (ME)	14	26%
	Technological-based (TE)	39	74%
		89	

Table 3. Percentage of papers linked to SF by scope and kind of contribution

Type of Contribution			**Supported Requirements**			
Engineering			**Which data?**	**Which access?**	**Which actors?**	**How to choose technologies?**
Fundamental Approaches	**ME**	25%	14%	8%	0%	0%
	TE	50%	6%	11%	0%	0%
Complementary approaches	**ME**	6%				
	TE	19%				
Total by category			20%	20%		
Implementation			**Supported Functionalities**			
Fundamental Approaches			**RT data collection**	**RT data distribution**	**RT data access**	**Assistance**
	ME	25%	2%	2%	2%	11%
	TE	75%	8%	13%	2%	21%
Total by category			10%	15%	4%	32%

Table 4. Distribution of SF papers by kind and scope of approaches according to the nature of SF contributions.

Regarding the engineering scope, the works are mainly technological based (69% in total) split in fundamental (50%) and complementary approaches (19%). The approaches treat two requirements: (1) the data definition and (2) the data-access definition. The choice of technologies and the actor definition are not treated by any research work. Regarding the technologies that are employed in major engineering developments, the CPS/CPPS is the most significant (39%) followed by the Internet of Things (IoT) (33%), Sensor Networks (SN) (17%) and Service-oriented Architecture (SoA) technology (11%).

Likewise, for the implementation scope, the contributions are mostly technological based (74%). The Assistance support (21%) and real-time data distribution (13%) are the most treated aspects.

4.3 Smart Factory Research Work Analysis and Synthesis

Based on the analysis performed we conclude that the Engineering-driven works are mostly technological based. From this perspective, it is possible to engineer the SF if the technology has already been set. Thereafter, we found mainly propositions enabling to define the data and the access to data, both key functions of the SF development. For instance, some layered architectures are proposed allowing to define the type of data retrieved and the data access settings like in (Kalaboukas et al. 2013; Hirmer et al. 2017; de Brito et al. 2016). However, the aspect linked to the definitions of which actors will be supported is not detailed.

On the other side, the methodological-based approaches do not deal with the design of SF in its globality. They propose modelling approaches and languages enabling to deal with the specificities of agility and adaptability in SF such as in (Fischer *et al.*, 2013) and in (Seiger *et al.*, 2015). Furthermore, for these design approaches, several questions remain open such as how to choose the technologies to be implemented for a given SF, how SF design should provide support to the actors of the manufacturing system, how the data retrieved can be integrated into the organizational context, particularly into the Information System (IS) or how to manage the transition from the 'AS-IS' to the 'TO-BE' smart manufacturing system. This last two issues are consistent with the conclusions drawn by Strozzi et al. (2017) who analyse systematically SF literature. However, their work does not provide nor an overview of the SF definition neither a general picture of the related research works. They remain at a global analysis level of the bibliographic network analysis (citation network analysis, global citation score analysis, author keyword analysis) providing, in this way, a first insight of the works of SF.

The works dealing with complementary aspects of engineering are miscellaneous contributions mainly centred on specific scenarios of SF in a particular field as in the work of Kassner *et al.* (2015) dealing with automated exception handling, the safety operation of CPS for different applications including SF in (Nicklas et al., 2016), or the study for petrochemical sector made by Li *et al.* (2015) with a relevant description of required key technologies for SF. This can be useful to develop a similar work for the general industrial sector, requiring however a deep generalization contribution.

Second, regarding the Implementation-driven approaches, mainly technological-based contributions are provided in order to implement the main functionalities of SF: real-data collection, real-time data distribution, real-time access and assistance support. The technologies identified are recurrent: CPS, IoT, SoA, WSN. Contrary to the engineering scope, the assistance provided to the workers is the most developed functionality. As a result, many systems are developed to improve the assistance in different areas (production issues, robots) such as integrating touch screen in the multi-agent based architecture of Tyrin *et al.* (2012), the virtual platform to remotely design, test and operate robots in (Galambos *et al.*, 2014), and more recently, the indoor location based SF platform in (Jo *et al.*, 2017). Regarding the methodological-based contributions, the focus is rather on approaches enabling to evaluate a given technology such as in (Syberfeldt *et al.*, 2017) for augmented reality smart glasses. In conclusion, this category is very rich, showing that the research in SF focuses on the way to implement the SF without providing global approaches and methodologies enabling to develop a SF in a holistic way in the company.

5 Industry 4.0 Literature Analysis

5.1 Industry 4.0 Definitions

The concept of I4.0 is introduced in 2011 at the Hannover Messe in Germany and its ideas published at that time in (Kagermann *et al.*, 2011). Then, in 2013 the German National Academy of Science and Engineering release the Industry 4.0 manifesto (Acatech, 2013).

According to some authors as (Anderl, 2015 ; Drath et al., 2014 ; Fang, 2016 ; Lasi et al., 2014 ; Leyh *et al.*, 2016 ; Weyer *et al.*, 2015 ; Zhou *et al.*, 2015), there is a clear consensus on the I4.0 term as referring to the fourth industrial revolution led by intelligent manufacturing era upon the trend of digitalization and essentially linked to the implementation of CPS.

To understand the concept of I4.0, we first present and analyse a group of definitions presented in a chronological way and on which we ground to propose our own definition of the concept. One of the first definitions of I4.0 we found is from 2014. Thus, Lee *et al.* (2014) states that I4.0 concept is "*hinged on the adoption of geometrical advancement in Information Technology (IT) and collaboration for the purpose of establishing manufacturing enterprise having the ability and potency of self-awareness, self- prediction, self-comparison, self-reconfiguration and self- maintenance".* Then, Drath et al. (2014) point out that Industry 4.0 is "*the triad of physical objects, their virtual representation and services, and applications on top of those".* Both definitions are focused on the use of technologies. The first emphasizes the potential benefit of IT to obtain self-x capabilities whereas the second details what is actually the core of CPS functionalities. Later, Shafiq *et al.* (2015) provide a definition of I4.0 stating that "*Industry 4.0 is the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes*".

With regard to the relation with SF, Zhou et al. (2015) argue that I4.0 "*encapsulates future industry development trends to achieve more intelligent manufacturing processes, including reliance on Cyber- Physical Systems (CPS), construction of Cyber-Physical Production Systems*

(CPPS), and implementation and operation of smart factories". Furthermore, Hermann *et al.* (2016) argues that "*Industry 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industry 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real time. Via Internet of Services (IoS), both internal and cross organizational services are offered and utilized by participants of the value chain"*. Here, the CPS application clearly appears with additional technologies such as IoT and IoS, whose implementation ranges from system production to the value chain of the company. Besides, the term SF is associated to this context.

Another aspect of I4.0 is developed in the definition of Leyh et al. (2016). It is linked to the plan draft by German government. It points out the lack of a universal definition and emphasizes the shift from centralized production to a flexible and self-controlled one, and adds "*within this production the products and all affected systems, as well as all process steps of the engineering, are digitized and interconnected to share and pass information and to distribute this along the vertical and the horizontal value chains, and even beyond that in extensive value networks"*. Hence, sharing information across the company and among involved enterprises of the value chain is the key element to attain a flexible factory. Similarly Hecklau *et al.* (2016) describes I4.0 as the *"increasing digitization of the entire value chain and the resulting interconnection of people, objects and systems through real time data exchange"*. Resulted intelligence of products, machines and processes, as they add, allows for independent adaptation to spontaneous changes of the environment.

Finally, Li *et al.* (2017) also converge on the fact that the I4.0 is considered as the introduction of the CPS –that communicates using IoT, data and services– within the context of smart factories.

From previous definitions, we can observe that I4.0 leverages essentially the use of technologies, the CPS at the core. Thereby, I4.0 enables the creation of virtual copies of the physical objects and the whole plant. Based on this, information from virtual representations is widely disseminated to achieve easy adaptation of the factory. Moreover, some authors such as

Leyh et al. (2016) and Hecklau et al. (2016) point out the benefit of such interconnectedness that goes beyond production system, impacting also value networks.

As a result of this analysis, the I4.0, in our view, concerns the manufacturing enterprise including manufacturing processes and engineering (Leyh et al., 2016) for self-X capabilities (Lee, Kao, and Yang 2014) through real-data exchanges based on CPS, CPPS and other IT (Drath et al., 2014). For the manufacturing system, I4.0 relies on CPS based smart factories (Li et al., 2017). The underlying objective is to impact all the value chain of the company (Hecklau et al., 2016).

5.2 Characterisation of Industry 4.0 Research Works

We review 472 eligible papers (articles, conferences and reviews) resulted from the main query of I4.0 (573 papers) and considering exclusion of the very total of 73 papers from the combined queries regarding the I 4.0 and a set of 28 works with either unavailable abstract or out-of-our scope research topic. As for the previous concepts, we characterize the research works by scope and kind of contribution (See Table 5). Moreover, we add two categories one for the works treating learning issues and one for review papers. These two latter types of papers are not reviewed in this study since we focus on the discovery and analysis of engineering or implementation approaches based on methods or technologies.

Then, each contribution is analysed according to the 6 key features extracted from the definition of I 4.0. Indeed, according to this definition I4.0 concerns (i) interconnection & communication of manufacturing and engineering processes for (ii) self-x capabilities based (iii) on CPS/CPPS or (iv) other ICT with an impact on (v) value chain and (vi) sustainability in (vii) a secure way (See Table 6). A single contribution could contribute to several features.

From the 472 articles reviewed, the outcome of engineering-oriented contributions for I4.0 is 33%. These are mostly based on methodologies. As a result, the Implementation domain represents 57% of publications. Learnings and Reviews have both small percentages with respectively 7% and 3% as seen in Table 5.

Contribution Scope/Kind of contribution		Total	Total %
Engineering		156	33%
	Methodological-based (ME)	118	76%
	Technological-based (TE)	38	24%
Implementation		268	57%
	Methodological-based (ME)	114	43%
	Technological-based (TE)	154	57%
Learning		34	7%
Reviews (Rw)		14	3%
Total		472	

Table 5. Percentage of papers by scope and kind of contribution

		Contribution Features							
Contribution's types		CPS/ CPPS	Self-X capabilities	Other ICT	Interconnection & Communication	Value Chain /Value Networks	Sustainability	Secure systems & data protection	**Total**
Engineering		**17%**	**5%**	**23%**	**30%**	**17%**	**5%**	**4%**	**100%**
	ME	12%	4%	14%	25%	15%	4%	2%	76%
	TE	5%	1%	7%	5%	2%	1%	2%	24%
Implementation		**7%**	**11%**	**44%**	**18%**	**11%**	**5%**	**4%**	**100%**
	ME	3%	7%	13%	6%	8%	4%	2%	42%
	TE	4%	4%	31%	12%	3%	1%	2%	57%
Review		**7%**	**0%**	**43%**	**7%**	**7%**	**36%**	**0%**	**100%**

Table 6. Distribution of papers according to contribution features of I 4.0 identified.

5.3 Industry 4.0 Research Work Analysis and Synthesis

First, from the analysis we performed we deduce that for engineering-driven works the contribution are mostly methodological based. These contributions focus on four main features of I4.0: interconnection & communication between manufacturing and engineering processes, value chain & value network integration, other ICT and CPS/CPPS.

For the first category, the articles generally deal with the digitalisation issues linked with I4.0 and their impacts on product and manufacturing engineering. For example, Gruender (2017) formalises the changes in product development required in a context of digitalisation. In the same line, (Shafiq *et al.*, 2017 ; von Leipzig *et al.*, 2017) provide approaches for virtual manufacturing environment and digital transformation of companies. From a complementary point of view the framework of Bucker *et al.* (2016) considers the development of a strategic plan to implement a defined I4.0.

Concerning value chain integration, the focus is mainly on efficiency of I4.0 trough lean principles. For example, Doh *et al.* (2016) propose to exploit lean manufacturing principle to meet the I4.0 requirements. In a similar way, Wang B. *et al.* (2016) develop the concept of LIPS (Lean Intelligent Production System) that exploits, for I4.0, value stream analysis. Another aspect deals with the link between I4.0 supply chain like Klumpp (2017), who provides an evaluation scheme for crowdsourcing in logistics enabling the development of new business models.

Last but not least, the works on other ICT and CPS/CPPS are the most numerous. In the other ICT category, researches generally deal with the way to integrate cutting-edge technologies, beyond CPS/CPPS, that converge with manufacturing technologies. Some of them provide assessment methods such as in (Rennung *et al.*, 2016) to assess service-networks in an I4.0 context or in (Wu *et al.*, 2017) that focus on cloud-based software for digital design and manufacturing. These approaches do not provide clear basis on how to select such technologies. An interesting approach is, however, found in (Flatscher *et al.*, 2016). It aims to help stakeholders over strategical technological planning but needs to be adapted to the specific company context. Besides, this methodology is applied rather to the production level than to the business level.

In the CPS/CPPS category several aspects enabling the engineering of such systems are developed. We notice two main aspects. First, the one dealing with the modelling, simulation and validation of CPS such as in (Galaske *et al.*, 2015) that develop models for deviation management in CPPS or in (Peres *et al.*, 2017 ; Voscek *et al.*, 2017) that focus on dynamic simulation and hybrid modelling. Second, the most widespread one, deals with the development of architectures that are proposed to configure and deploy CPS with the main goal of delivering high resolution production control as in (Stich *et al.*, 2015). Most of these works are linked to the use of big data technologies to perform advance analytics in this context as in (Seitz *et al.*, 2015). In this context, there is little emphasis on how to manage the successful introduction of the CPS into traditional enterprises in compliance with operating information systems and organizational requirements associated. However, the work of (Fantini *et al.*, 2016) investigates the role of human in CPPS with two integration models human-in-the-loop and human-in-the-mesh.

Secondly, the implementation support of I4.0-complied systems is vast. They represent more than 50% of the paper we retrieved and are almost technological-based. Contrary to the engineering driven contributions, the CPS/CPPS category represents only 7% of the papers. Most of the contributions concern the following features of I4.0: other ICT, interconnection & communication between manufacturing and engineering processes, value chain & value network integration and self-X capabilities.

In the other ICT category, the emphasis is on development on ICT to enhance the engineering and production tasks: particularly sensors and IoT as enablers of the CPS, but also SoA, cloud computing, big data and augmented reality. For example, one can cite (Chaves *et al.*, 2016) that deals with setting up of low cost sensors or (Liu *et al.*, 2017) that focus on how cloud manufacturing can contribute to I4.0. Similarly to SF, most researches deal with specific problems from defined technological configuration. More holistic approaches are still required to manage the choice of the ICT to be implemented.

For the interconnection & communication between manufacturing and engineering processes, apart from the techno-centred contributions, the works develop approaches to improve the integration between manufacturing and engineering like in (Ferreira *et al.*, 2016) with an integrated PLM architecture.

For the last two categories, there are fewer works. Thus, the articles in the value chain & value network integration are mainly related to the way to implement lean philosophy and I4.0 such as in (Huang *et al.*, 2015 ; Meudt *et al.*, 2017 ; Tonelli *et al.*, 2016) considering value chain and value network integration from a very specific point of view that could be enlarged. Last but not least the implementation of self-X capabilities are mainly linked to the sustainability of a given company such as in (Prause *et al.*, 2017 ; Waibel *et al.*, 2017).

For implementation whatever the considered category is the role of human is seldom taken into account even it is claimed that the growing complexity of the implemented technologies requires specific skills. This is underlined in (Kamensky, 2017) that focus on the social paradox of I4.0.

6 Relations and links among FoF, SF and I4.0

Based on the three states of the art made previously, in this section, the question is how FoF, SF and I 4.0 relate to each other? In other words, what are the similarities, common characteristics but also differences of each concept? How to combine them in order to carry out the industrial transformation desired? To answer these questions, we first, highlight the complementarities of FoF, SF and I4.0 based on the definition of each concept that we give in section 3.1, 4.1 and 5.1. Second, we analyse the combined queries that provide a global view of the actual research trends. In a first instance, the Venn diagram in Figure 3 underlines the correlations between the three concepts.

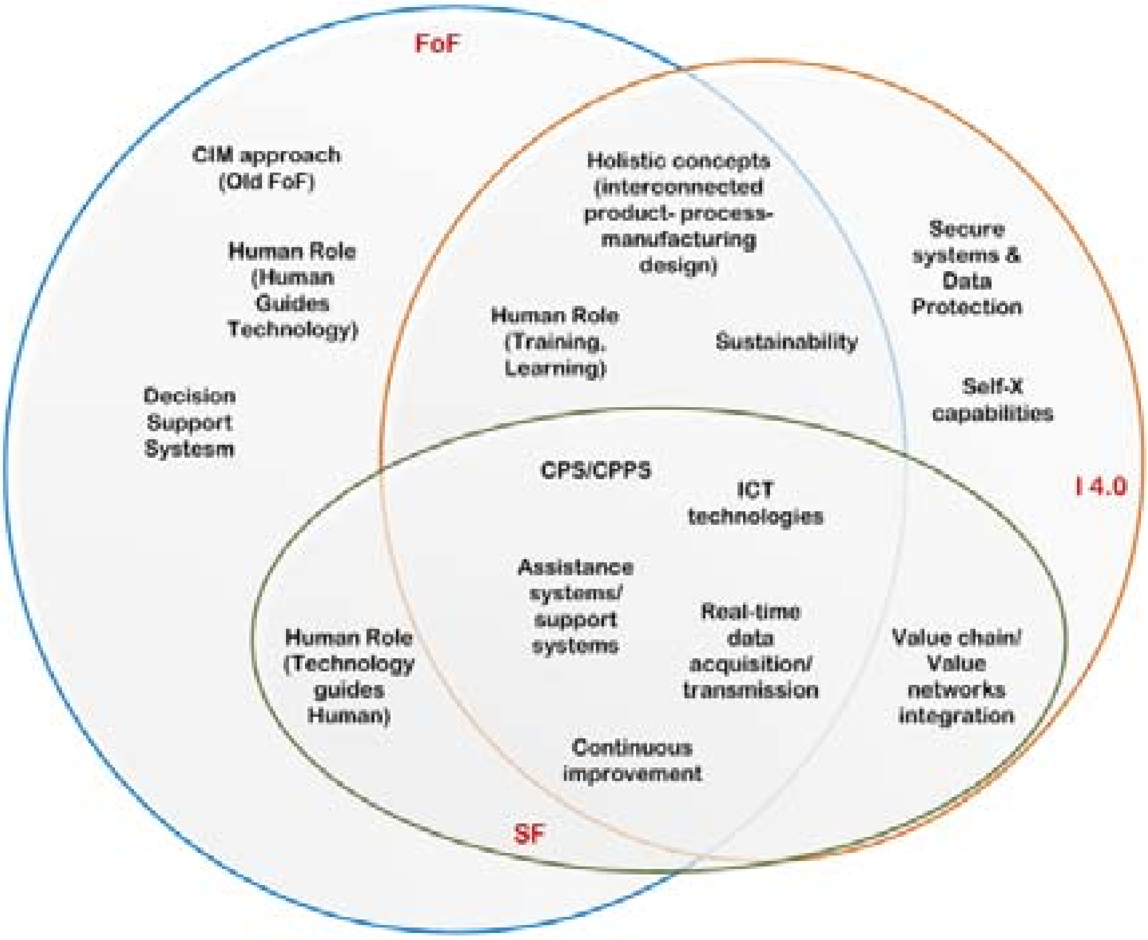


Figure 3. Similarities or common features among FoF, SF and I 4.0

6.1 Correlations based on the definitions

FoF denotes a concept that represents a long-term evolutionary process encompassing the organizational demands that industrials have had to address since the emergence of computer-based integration. IT underlines the key-features a factory has to have in the future. Among these features, one can notice highly integrated, organized and intelligent control of the production chain (Simsek et al., 2004 ; Welber A. , 1987) ensuring high added value and sustainable products and services (Bathelt et al., 2010 ; Jufer et al., 2010).

Secondly, Smart Factory underlines one of the key-feature of a FoF its “intelligence” or “smartness”. Contrary to FoF, this concept goes beyond the features of the factory and emphasizes the required abilities to be smart. They lie on real-time collection, distribution, and access to manufacturing information.

Thirdly, I4.0 has a wider scope than FoF and SF as it concerns not only the factory but the company and its value chain in a whole. To succeed in self-X capabilities and real-time data exchanges are claimed. This becomes possible through the intensive use of ICT such as CPS and IoT. In our view, the objectives behind I4.0 factory, which is a part of I4.0, constitute the actual FoF features. In this context SF enables real-time data exchanges and finds naturally its place in the I4.0 context to allow real-time monitoring as well as adaptation and continuous optimization of processes (Sun *et al.*, 2017 ; Xu *et al.*, 2017 ; Zheng *et al.*, 2017).

6.2 How to combine FoF, SF and I4.0?

To give an overview of the potential combination of FoF, SF and I4.0 the results of the combined queries offer a quantitative measure of this relationship (See Table 1). These are ranked in descending order as follows:

1) SF-I4.0 (62 papers),
2) FoF-I4.0 (14 papers),
3) FoF-SF (8 papers),
4) FoF-SF-I 4.0 (5 papers).

These results are consistent with the analysis of each concept and its links we make in the previous sub-section. We address above the main correlations among the three concepts. Here we bring some discussion related to closer features that relate SF-I4.0, FoF-I4.0 and FoF-SF:

1) *SF-I4.0 relation*: this relation is the most tackled in the literature. It deals with the technologies that enable smarter production in an I4.0 context. Of course CPS remains the main technology like in (Ahmed *et al.*, 2015 ; Fleischmann *et al.*, 2016 ; Thoben *et al.*, 2014b). In these works various aspects are treated like requirements engineering for CPS (Wiesner *et al.*, 2014) or the monitoring challenges linked to CPPS (Zinnikus *et al.*, 2017). Other technologies such as IoT (Zhong *et al.*, 2017) and big-data to deal with the collected-data (Wang S. Y. *et al.*, 2016) are also in the centre of the research works we analyse. Moreover, the SF-I40 tends to give an important place to the human role and particularly to the workers. So, the role of virtual reality

to support workers is analysed in (Paelke, 2014). In (Brauner *et al.*, 2015) the role of human factors in a I4.0 and SF context is studied, whereas in (Park *et al.*, 2017) the way I4.0 and SF can improve workers security is detailed.

2) *FoF-I 4.0 relation*: Most recent researches tend to position the FoF and the I4.0 in a similar angle focusing on connected and intelligent manufacturing systems. As such the actual view of FoF represents the factory part of I4.0. The related researches we retrieve focus on three main complementary topics. First, as usual, several works are dedicated to the development of technological means to support the implementation of such manufacturing systems. One can cite (Sepulcre *et al.*, 2016) focusing on protocols for wireless networks or (De Coninck *et al.*, 2016) who develop a middleware that abstracts the deployment of service-based CPS software components on a distributed platform comprising robots, actuators, sensors and the cloud. Second, when dealing with the FoF-I4.0 relation several authors study the challenges and the way to manage the transition towards I4.0. In this context, (Jardim-Goncalves et al., 2017) analyse five board topics enabling to switch towards intelligent manufacturing systems. These topics entail, among other, the pervasiveness of Cyber-Physical Systems; the Virtual Organisation (VO) of manufacturing systems and the servitisation of manufacturing systems. In the same vein, (Kannan *et al.*, 2017) focus on the gap between current MES (Manufacturing Execution System) functionalities and these required by I4.0. Third, the FoF-I4.0 relation brings main attention on training of the workers involved in manufacturing systems embedding new technologies and new way of working. For example, (Richert *et al.*, 2016) present theoretical aspects and empirical results linked to the competencies required in virtual collaboration and joint problem solving in virtual worlds. (Gorecky *et al.*, 2017) reports on virtual learning environments and (Karre *et al.*, 2017) present a learning factory.

3) *FoF-SF relation*: there are few works that deal both with FoF and SF. This is consistent with our previous analysis as SF can contribute to FoF and by developing its smartness. In the works we retrieve in this category, the FoF-SF relation is mainly considered from a technological point of view and their potential support to workers. So, (Syberfeldt *et al.*, 2016) review the techniques enabling to locate operators in a plant. (Syberfeldt et al., 2017) focus

on augmented reality as a way to support decision making in the shop-floor. In (Herwig *et al.*, 2017) IoT is analysed for holistic digital planning.

4) *FoF-SF-I4.0 relation*: the works that entail simultaneously the three concepts are very general one focusing on the research challenges linked to I4.0 such as in (Preuveneers *et al.*, 2017). These authors underline the notion of intelligent environments creating smart personalized products through smart processes and procedures.

7 Conclusion and Research Perspectives

The research review conducted in this work tries to make a step ahead in the urgent need to guide industrials through the landscape of concepts used for denote the new era of industrial manufacturing. Our research review was conducted to gain a clear understanding of the specificities and complementarities of the FoF, SF and I4.0 concepts. Based on an iterative literature analysis process, we categorize the contributions according to their scope: engineering, implementation and their kind: methodological-based and technological-based. We analyse them to give a general picture of the works belonging to each concept. Moreover, for each concept we propose a consensual definition enabling us to work out the frontiers between them and propose some complementarities.

From this work we can conclude the three concepts are somehow complementary as they have different scope. The current trend is to move towards I4.0 that concerns the company as a whole and not only its manufacturing system. For this part, I.4 can rely on SF that represents the main features of the "today" FoF. In this mainly technological driven context, several research stakes remain.

There is a need for global approaches enabling companies to manage their transition towards I4.0. To succeed in the co-evolution paradigm as detailed in (Tolio et al., 2010) seems to be relevant. It considers that all the sub-systems involved in the transition have to evolve accordingly. However, the initial proposition of (Tolio et al., 2010) is too coarse to support co-evolution management. In our view, a detailed co-evolution model as well as an operational exploitation process is required.

According to our analysis, the co-evolution model has, first, to take into account the strategical, tactical and operational dimensions of change to ensure a global value chain improvement. Second, the place and impacts on human work and related skills are also crucial. One research stake is how to model this aspect.

Chapter 3.

Factory of the Future: The industrial transition through the prism of co-evolution

1 Introduction

In order to fully realize their potential, modern organizations have stepped up their efforts to bring better practices and advanced performance for industrial evolution associated to the concepts of Factory of the Future (FoF) (Welber I., 1987), Smart Factory (Lucke *et al.*, 2008b) or even Industry 4.0 (Drath et al., 2014). A big issue for organizations is to manage this transition from a given situation towards a target evolved scenario. The promise that parallels this transition is set against a wide range of technological, organizational and societal challenges (Thoben *et al.*, 2014a).

In the last decades, research agenda have been devoted to develop new methods, techniques and tools to master the transformation of industries. These works however have been mainly devoted to techno-centred issues, and rather less attention has been paid to a global engineering approach. Research is still necessary to propose and validate paths and methods of implementation (Moeuf *et al.*, 2018) including organizational needs to include human resources (Pereira *et al.*, 2017) and Information Systems (IS) (Haddara *et al.*, 2015).

In this line of action, the model that Tolio et al. (2010) have developed is promising as it provides the basis for understanding the problem of co-evolutionary relationships within the industrial context. From this viewpoint, these cause-effect relationships have to be formalized so that companies are capable to adapt to new dynamics involved in highly competitive contexts alike FoF's. As such, co-evolution can lead to explore and build potential interactions within an organization. In this study, we are interested in co-evolution as a mean to successfully exploit these interactions to orchestrate the desired transformation.

We draw on the prior work of Tolio et al. (2010) which focuses on co-evolving product, process and production systems. Despite the authors provide a detailed description of the existing approaches and methodologies to tackle co-evolution, the model they propose limits itself the scope of co-evolution to the basic activity of processing inputs to obtain outputs. It thus neglects the complex domains in which firms can also seize future opportunities in their competitive business involving the product design and information system set-up. Moreover, the model lacks the explicit representation of strategic decisions on which these management choices rely (i.e. to match the firm's business with the dynamics of the environment) (Karimi, 1988 ; Papadakis *et al.*, 1998).

As such, the co-evolution model as initially worked out in (Tolio et al., 2010) needs to be completed in order to best suit the need of firms to deal with adaptation when its competitiveness is at stake. Therefore, in the present paper we aim to complete the proposed co-evolution model by identifying and developing the missing elements required to perform co-evolution as a path to achieve a desired industrial scenario.

To do so, the paper is structured as follows. In section 2 we detail the original model. We also discuss its strengths and limitations to deal with the co-evolution management as required for the transition to the factory of the future and how the model can be adapted to this objective. In section 3, we first modify and complete the original model by exploiting the Strategic Alignment Model (SAM) (Henderson et al., 1993) and the related work of Avila *et al.* (2008) about the E-SAM. Then, we detail the content of this model with the corresponding enterprise modelling constructs stemming from ISO 19440 (2007). Conclusions and perspectives are drawn in section 4.

2 Initial co-evolution model analysis

2.1 Co-evolution model overview

The work of Tolio et al. (2010) is based on the “co-evolution paradigm”. This paradigm is defined as: “the repeated configuration of products, process and production system over time”. To manage co-evolution, they proposed a model that allows to delimit a space where co-evolution management approaches, tools and problems can be mapped.

The model takes a geometrical shape represented by a triangular prism (See Figure 4). The edges of the prism stand for the three “configuration entities” (P3S): products, process and production system. The prism includes a vertical axis to represent the evolution axis. At any level of the evolution axis, the triangular cross-section represents the integration space among the three entities.

2.2 The co-evolution management process

The co-evolution management process of the original co-evolution model is considered as a configuration activity of the product, process and production system entities. The authors propose two metrics to evaluate a given configuration approach enabling to choose the one fitting the best to a specific configuration context. These metrics are the integration level and the evolution level. The integration level aims to analyse the way a given approach enables to work out a configuration solution. It is mapped within the integration space of the model.

The evolution level is the capability of a configuration approach to take into account potential evolutions of the entities. It is mapped at the vertical axis through check points in order to evaluate the configuration approach at a given time period.

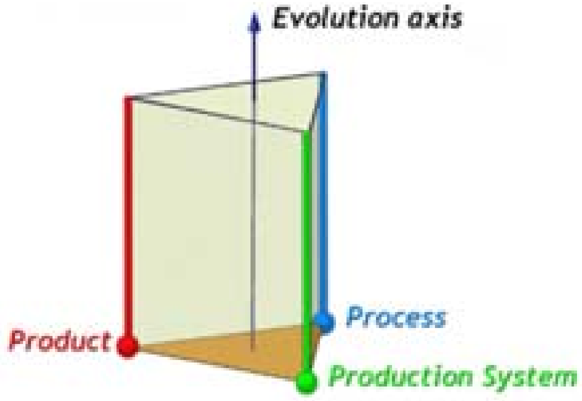


Figure 4. Graphical representation of the co-evolution model (Tolio et al., 2010)

2.3 General analysis and conclusions concerning the co-evolution model

As previously mentioned, Tolio et al. (2010) consider co-evolution as the repeated configuration of the product, process and production System entities. The authors show that this co-evolution is crucial in environments subject to continuous changes like FoF's context, in which we are interested. The related management consists in choosing the configuration approach fitting the best to a given situation. In other words, the co-evolution model they propose is used to map and analyse existing configuration approaches. This provides a global overview of the existing approaches but does not provide an effective support to manage the potential interactions between the entities to be configured.

Therefore, in our view, the co-evolution model can be exploited to manage these interactions. Within a consensus-based perspective of management scholars, it can help to understand and manage the multi-level interactions that explain competition and change across the organization, considering also their interdependencies like found in biological evolution (Abatecola *et al.*, 2016 ; Penn *et al.*, 2018). However, if the co-evolution is used in this sense, the entities subject to configuration have to be further detailed. In the initial proposal the definition of the product, process and production system entities are very coarse and do not detail the specificities required to make design decisions related to each entity, including the correlations among them and with respect to higher decision levels of the organization. Furthermore, although the authors recognize the role of manufacturing strategy, the strategic dimension is still not depicted in the model. Indeed, they do not consider it as a driver but only as a controller once a configuration solution has been applied.

Therefore, in order to guide the co-evolution towards FoF's, we aim to complete the proposed co-evolution model with the following aspects that we consider necessary to address: 1) the explicit consideration of the role of the Information System (IS) within the model, not only from its the technological function (i.e. IT functionality) but from its key role at the centre of the major managerial functions adding value to the firm's processes and 2) the consideration of strategic dimension since it involves the pattern of decisions that leads the activities of the firm into a specific direction (Hayes *et al.*, 1984).

By developing these objectives, we argue that a more powerful co-evolution model is built which can be further applied as an effective management tool towards FoF's environment. The next section will explain the resulting restructuring of the model involving new domains' decision areas for both internal and external levels of analysis.

Particular attention should be paid to the underlying choices regarding the role of human. Choices of the human dimension namely their competencies and skills will be included in our co-evolution model. In the further discussion will also argue how our contribution can potentially cover the dynamics of choices concerning the development of human beings in response to the objectives of the changing organization.

3 The proposal of an enhanced co-evolution model

In this section, we present and detail the completed co-evolution model taking the model of (Tolio et al., 2010) as a starting point. To succeed in, we rely one:

- A detailed analysis of the P3S entities of the already defined model to set up the domains of our enhanced co-evolution model.

- The Strategic Alignment Model (SAM) of (Henderson et al., 1993) enabling to integrate the strategic dimension into our model.

- Enterprise Modelling (EM) techniques which provide means to describe process oriented systems and decompose them into manageable parts (Zelm *et al.*, 1995). We exploit the ISO standards for EM: ISO 19440 (2007) to define the modelling constructs required to represent the domains of our model.

3.1 Definition of the new domains of the co-evolution model

3.1.1 Redefinition of the P3S entities into domains of the enhanced co-evolution model

Our first concern aims at complementing the co-evolution view as depicted in the model which considers three basic entities: the product, the process and the production system. According to the definition of the entities, it is assumed that interactions only result from the transforming process that relates the input and the output of a system. As such, the model reduces the scope of co-evolution to the physical process through which an output, namely a product is obtained by means of a performed production system.

So, we consider this proposal as a preliminary effort that provides direction for addressing co-evolution to a broader context that complies better with the range of activities and decisions organizations have to deal with. In this context, we suggest to redefine the proposed entities into domains. Into each domain we can thus specify the set of decisions that should mutually co-evolve for enabling 'AS-IS' reengineering.

Moreover, by defining functional domains like product design, product manufacturing etc., their specific composition can be captured for domain's user request and possible interrelations can be clearly focused. From the Enterprise Modelling viewpoint this is a modular way allowing to deal with the overall system complexity (Berio Giuseppe *et al.*, 2001).

Therefore, two main domains are derived based on the entities of the original model:

- The Product Design domain is composed of the product entity. Nevertheless, we propose to expand the initial concept so as to consider the processes of product development like appropriate design methods which can affect manufacturing costs or productivity. Indeed, product design, both as an outcome and a process is relevant for organizational success (Chen, 2018).

- The Manufacturing domain bundles the process and the production system into the same domain. This is because both are closely related since they rely on each other to carry out the transformation for a product. The concepts emphasize this aspect as they define the process as the logical procedures executed by the production system and this latter as a set of resources and policies that in turn allow the execution of the processes.

3.1.2 Definition of the Information System (IS) domain of the enhanced co-evolution model

According to our objective we add the IS domain to tackle the decisions regarding the setup of the IS matching the needs of the enterprise. The IS has a key role on organization to support the execution of operational, managerial and executive-level processes. Furthermore, IS academics broadly agree that IS has to be considered as an entire functional domain on its own, being at the core of business process and Information Technology (IT) evolutions. As result, IS needs to be aligned with the business activity and new technologies in order to create value for the organization and effectively support innovation (Ferreira *et al.*, 2017).

3.2 Integration of the strategic dimension

Concerning the strategic dimension, we exploit the Strategic Alignment Model (SAM) proposed in (Henderson et al., 1993). This is one of the first frameworks that consider simultaneously the strategic and implementation levels of analysis. The authors detail these levels as follows:

- The external level, also called the ‘strategic level’ deals with the arena in which the firm competes, their attributes that differentiate it from its competitors, the decisions regarding product-market offering as well as “make-versus-buy” decisions, including partnerships and alliances.

- The internal level, also called the ‘structural level’ concerns the implementation choices related to the logic of the administrative structure and the specific rationale for the design and redesign of critical business process, and the resources to operate and manage it.

As the distinction made by the SAM, we split each domain of our co-evolution model into two levels: the internal level and the external one. The definition of the domains has to include the content of each domain to support co-evolution management as defined in section 2.3. This is done in section 3.3 exploiting the E-SAM proposed by Avila et al. (2008) which add two domains to the classical SAM: product design and production. These domains are similar to ours.

3.3 Internal structure of domains

The general sub-domain structure of the E-SAM is the same as the one of the SAM with three components per sub-domain: (1) The scope (or perimeter), competencies and governance in the external level; (2) The infrastructure, skills and process in the internal level. We use the same component structure for the six sub-domains of our co-evolution model because the decisions specified are common to the concerns we aim to tackle for the internal and external level of the co-evolution approach.

As a result, the Figure 5 shows the general structure of the proposed co-evolution model. The next section details the content of each component.

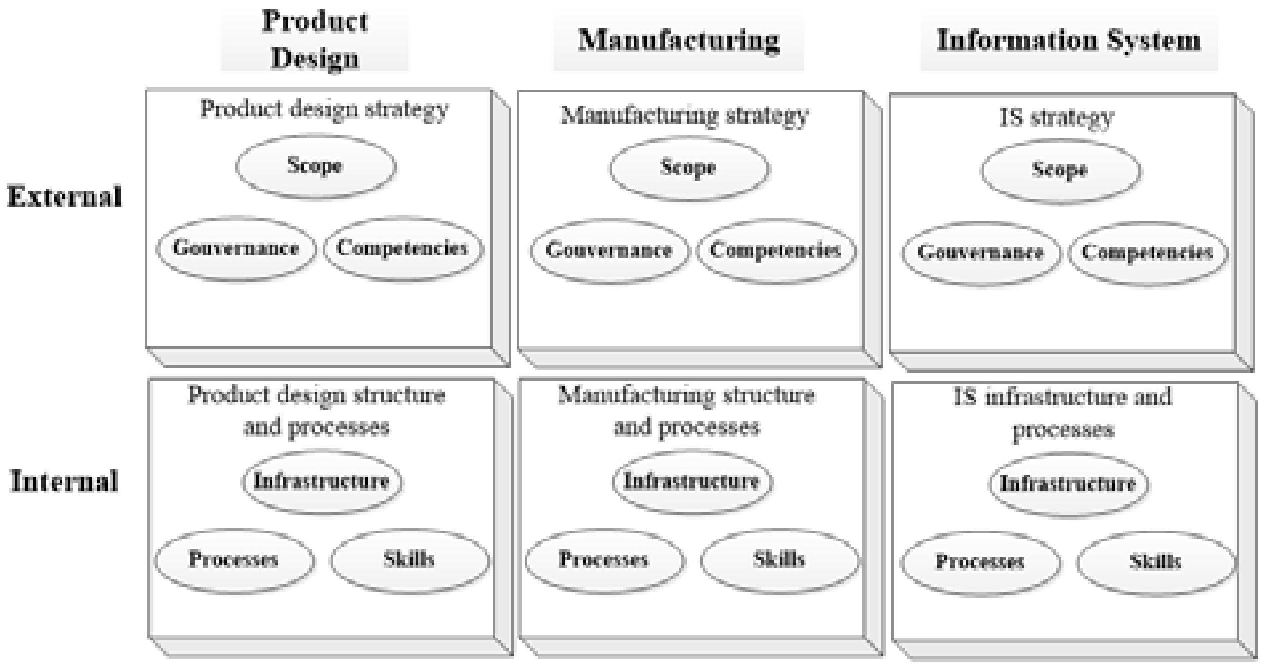


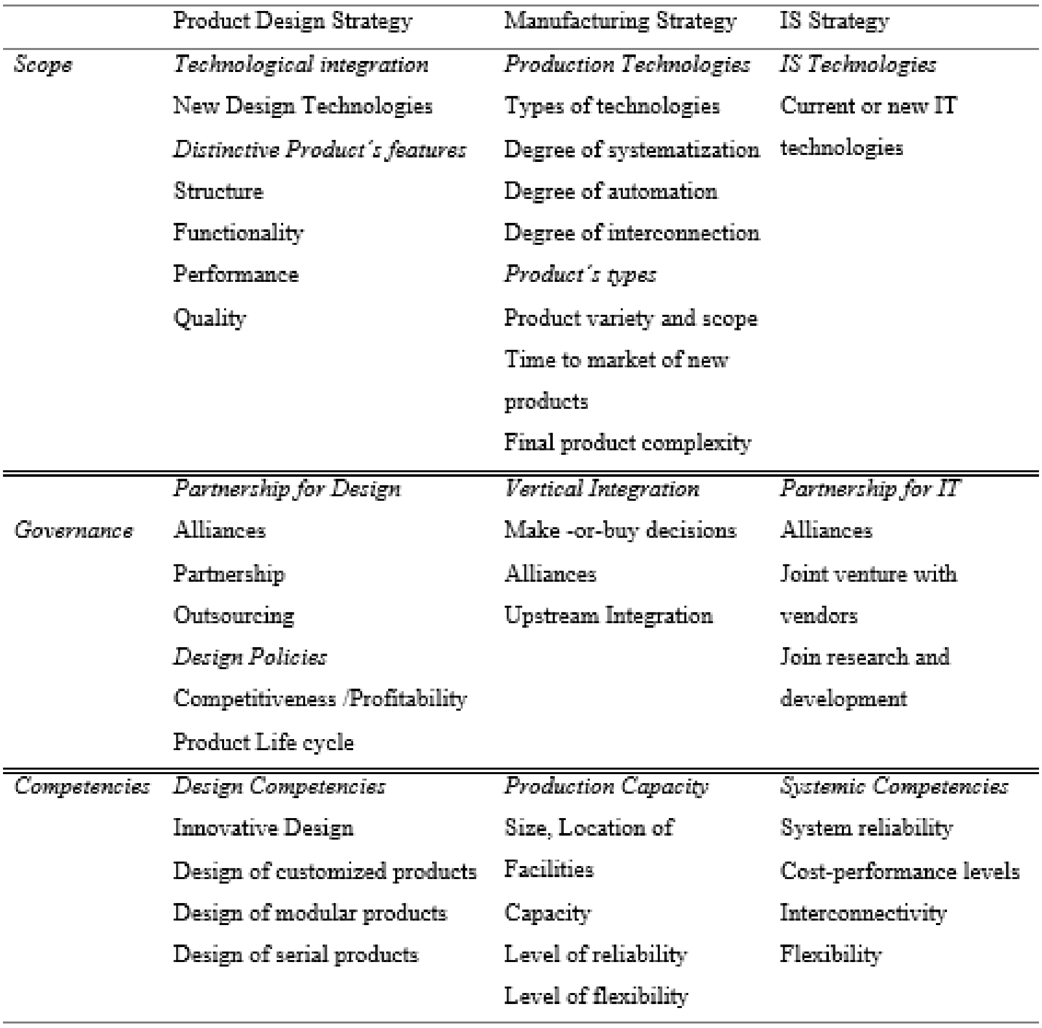
Figure 5. The detailed representation of the completed co-evolution model

3.4 Modelling the components of the co-evolution model

As the modelling purposes differ between the internal and the external level, the way to model them also differs.

3.4.1 Modelling of the strategical level of the co-evolution model

Since the external level is related to the strategies, their modelling must enable to represent the strategic behaviour of companies in the form of decisions or activities that are in harmony with the enterprise activities performed. This aspect is already tackled by the set of decisions of the domain's components within the E-SAM. So, for this level we exploit them as presented in Table 7.



	Product Design Strategy	Manufacturing Strategy	IS Strategy
Scope	*Technological integration* New Design Technologies *Distinctive Product´s features* Structure Functionality Performance Quality	*Production Technologies* Types of technologies Degree of systematization Degree of automation Degree of interconnection *Product´s types* Product variety and scope Time to market of new products Final product complexity	*IS Technologies* Current or new IT technologies
Governance	*Partnership for Design* Alliances Partnership Outsourcing *Design Policies* Competitiveness /Profitability Product Life cycle	*Vertical Integration* Make -or-buy decisions Alliances Upstream Integration	*Partnership for IT* Alliances Joint venture with vendors Join research and development
Competencies	*Design Competencies* Innovative Design Design of customized products Design of modular products Design of serial products	*Production Capacity* Size, Location of Facilities Capacity Level of reliability Level of flexibility	*Systemic Competencies* System reliability Cost-performance levels Interconnectivity Flexibility

Table 7. Decision-based modelling of strategic sub-domains of the co-evolution model

3.4.2 Modelling of the structural level of the co-evolution model

Co-evolution management requires structured modelling of the internal level. Therefore, we propose to exploit modelling constructs of EM defined in ISO 19440 (2007) by mapping them with the internal components of the co-evolution model, as they do not fit naturally into each other. For sake of clarity, we take guidance on a previous mapping identified in the work (Goepp *et al.*, 2014) between the components of the SAM and the constructs of ISO 19440 (2007). The results of our mapping are detailed in Table 8.

		Co-evolution model components at Internal level								
		Product Design			Manufacturing			IS		
	Modelling Constructs ISO19440	Design Structure	Design Processes	Skills	Infrastructure	Manufacturing & support Processes	Skills	Architecture	Processes	Skills
Function View	Domain		x			x			x	
	Business Processes		x			x			x	
	Enterprise Activity		x			x			x	
	Event		x			x			x	
Information View	Enterprise Object		x			x		x		
	Object view		x			x		x		
	Product		x			x				
	Order		x			x				
Resource View	Resource			x	x		x	x		x
	Functional Entity			x	x		x	x		x
	Capability				x			x		
Organisational View	Organisational Unit	x		x	x		x			x
	Organisational Cell	x								
	Decision Centre									

Table 8 Mapping made between the internal components of the co-evolution model and the Modelling language constructs from ISO 19440 (2007)

Following the results of the mapping, the first four constructs of the function view correspond to the processes of the product design, manufacturing and IS domain and are mapped accordingly. These four constructs: Domain, Business Process, Enterprise Activity and Event, represent the functional aspects of the enterprise, meaning their processes and activities.

The next four constructs of the information view involve information-related entities used and obtained during enterprise operations. The Enterprise Object and Object view constructs refer to the inputs and outputs of enterprise activities or enterprise object, respectively. As such, these constructs are mapped to the processes of our domains since they have to be defined for the process operation. They are also mapped to the architecture of the IS domain since they refer to the definition of the data architecture. Regarding the constructs of Product and Order, both are specializations of the Enterprise object construct. Concerning the Product, this construct is represented as the output of an enterprise's process. Products have to be described within the process component of the manufacturing and product design domain where it is mapped. The Order construct represents the 'information for planning and control of a business process in an enterprise'. It may be also the end-result of a business process used to describe a further activity. As a result, we map it to the process component of the product design and manufacturing for which orders have to be described.

In the resource view, the Resource construct and its specialization: the Functional entity construct describes required capabilities that any enterprise activity needs in order to take place. These include the equipment, facilities, people and organizational groupings, as well as equipment for data processing. As such, both resource and functional entity constructs are mapped to the infrastructure of manufacturing and IS. Operational capabilities or skills provided by a resource or required by the enterprise activity are also described here and are mapped to the skills component of each domain. Regarding the capability construct, it describes attributes related to the identified resources like constraints that have to do with processing such as tooling dimensions, data processing or time restrictions. As a result, the capability construct matches with the architecture of manufacturing and IS but it is not linked to the product design domain.

The organizational view represents the organization, organizational relationships and decision-making responsibilities in the enterprise operation. The construct of Organizational unit refers to the roles and responsibilities to perform human tasks within a given hierarchical structure. Thus, we map this construct to the skills component and the design structure of the product design domain. Similarly, the construct of Organizational cell is mapped to the design structure component since it refers to the hierarchical structure of an enterprise like divisions and departments. At last, the Decision Centre construct deals with decision system modelling. In our view, this construct is not linked to any modelling concern of the co-evolution model's components.

3.5 Considerations on human role from the resource view

One of the fundamental aspects to consider concerns the implications of organization' changes on human beings' skills and experience.

The importance of that matter has triggered the setting of an agenda in the European Union, which is known as the Lisbon Strategy, to achieve the most competitive and dynamic knowledge-based economy in the world. This agenda involves training and educating the workforce in order to acquire skills and competencies necessary to compete internationally by focusing on areas like science and technologies (European Council, 2000).

Despite the focus that some researches have put to this topic, they have not put forward specific tools to manage the effect that future industrial capabilities will have on human resources by creating new skills requirements. In our contribution, we aim to consider these aspects by exploiting the decision set of 'competencies' and 'skills' as defined in the E-SAM. As a result, we can address human's role by modelling it as a resource within higher and lower levels of the organization. For this purpose, we follow the modelling standard ISO 19440 (ISO 19440, 2007) through the predefined 'resource view'. The resource view allows to represent the roles and responsibilities of human resources. Thus, based on the established standard, we can integrate in the co-evolution model decisions of the profile required to perform a task, including the required capacities that must be fulfilled as skills and functions. In this way, we are able to handle the dynamics of the human's role in response to strategic and structural rearrangements. Moreover, we can consider the necessary alignment of the perceived skill's gap in relation with the desired state that the organization seeks to meet.

4 Conclusions and Perspectives

Organizations are struggling to keep the pace with evolutions whereby they have to make co-evolve their subsystems. That is why co-evolution becomes relevant in order to enact successful engineering changes while maintaining the coherence along the whole business structure. Relying on the work of Tolio et al. (2010), in this paper we have consolidated a co-evolution model with the aim to help firms to foster adaptation looking towards next-generation factories.

Taking the prior model as starting point, we have pointed out that co-evolution must take an integrated approach of the key interdependencies that can lead firms to change and adapt themselves to future contexts. As a result, our first contribution is to build up three key domains: product design, manufacturing and IS as the ones interacting within the prism of co-evolution. From a macroscopic view, the evolution axis represented by a vertical axis remains at the centre of the triangular prism with the redefined domains, in order to highlight the time dimension involved during co-evolution.

According to (Tolio et al., 2010), from a co-evolution stance, successful transition results from the strategic and operational management of engineering changes that propagate to the different levels of the organization. Consistent with this notion, we have defined two levels of analysis for each domain: the internal and external level. The interdependencies between each other, specifically the way they can be modelled and managed over the time are the main motivation behind this work. As a result, we have taken into account the strategic links that were missing. Furthermore, the role of human workforce can be addressed through the domain's content related to the competencies and skills of human resources. The definition of the two-level structure is made in analogy with the SAM (Henderson et al., 1993) while the content's detail of the resulting 6 sub-domains is based on the E-SAM (Avila et al., 2008).

Taking a step further in completing the co-evolution model, we have exploited the modelling constructs for enterprise models of ISO 19440 (2007). Hence, we have mapped the standard constructs to the content of the internal sub-domains. By making this we provide a common modelling representation that opens up further research on extending co-evolution for architectural contexts of an organization.

More importantly, the generic constructs related to the Resource view and the Organizational view allows us to describe and create instances of the profile skills that human beings deliver. As such, the impact of human factors can be considered in the co-evolution from the current to the desired state. Furthermore, a further development could be pursued by refining constructs in the Resource view to include specific management concerns related for example to the planning of the personnel or the assignment of the workplaces.

To effectively support co-evolution management, we will further choose relevant modelling languages to formally represent the processes of the internal sub-domains. For instance, BPMN (Business Process Modelling Notation) (OMG, 2013) and UML (Unified Modelling Language) (OMG, 2017) are both widely recognized standards with support from many tools. The first one focuses on business process modelling including visual description like workflows that allows to analyse the business process in detail. As such, BPMN can efficiently drive the translation from the conceptual design to their implementation. The second modelling language, UML, supports software applications and software architecture modelling.

The precedent efforts represent the first stage of our work. In further steps we will consider the managerial implications that can arise from the instantiation of the co-evolution model related to a current and future organization state (i.e. “AS-IS” and “TO-BE” states). To do so, we aim to identify potential relationships across the domain’s models, meaning domain-to-domain interactions as well as those between their internal components. Further, we will characterize these interactions and build “co-evolution sequences” in terms of the attributes of the specific relationship (i.e. the direction from one specific domain to another) and their degree of impact (i.e. poor, necessary, insufficient). Empirical evidence will be necessary to validate the completed co-evolution approach.

Chapter 4.

Analysis of the links existing among the domains of the co-evolution model

1 Introduction

Among the three domains and two levels composing the co-evolution model, different kind of links or relationships can be identified. We are interested in identifying these relationships as they could represent the way domains co-evolve and in turn how this co-evolution can be guided or managed.

Therefore, three types of links can be defined according to the domains and the levels they involve. These links are named in analogy to the Strategic Alignment Model (SAM) (Henderson et al., 1993) which define them as (cf. Figure 6):

1) *Strategic fit* linking both levels of the same domain. This link is detailed as strategic fit and reverse strategic fit; each one referring to a different level direction (from the external level to the internal one and vice-versa),

2) *Functional integration* linking two domains at the same level. This link is detailed as strategic integration and operational integration, each one referring to a given level (external and internal respectively) and

3) *Automation linkage* where two different domains of different levels are linked. This type of link is out of consideration as such in our work since it is incompatible with the execution of hierarchical decisions in the enterprise context. This is consistent with the rules provided by the GRAI grid (Graphs with Results and Actions Inter-related) (Doumeingts, Vallespir, & Chen, 1998).

The next sections are dedicated to detail the strategic fits and functional integrations we consider in our model. The objective is to define conceptually each kind of link and to illustrate each specific link through examples stemming from works that deal with them.

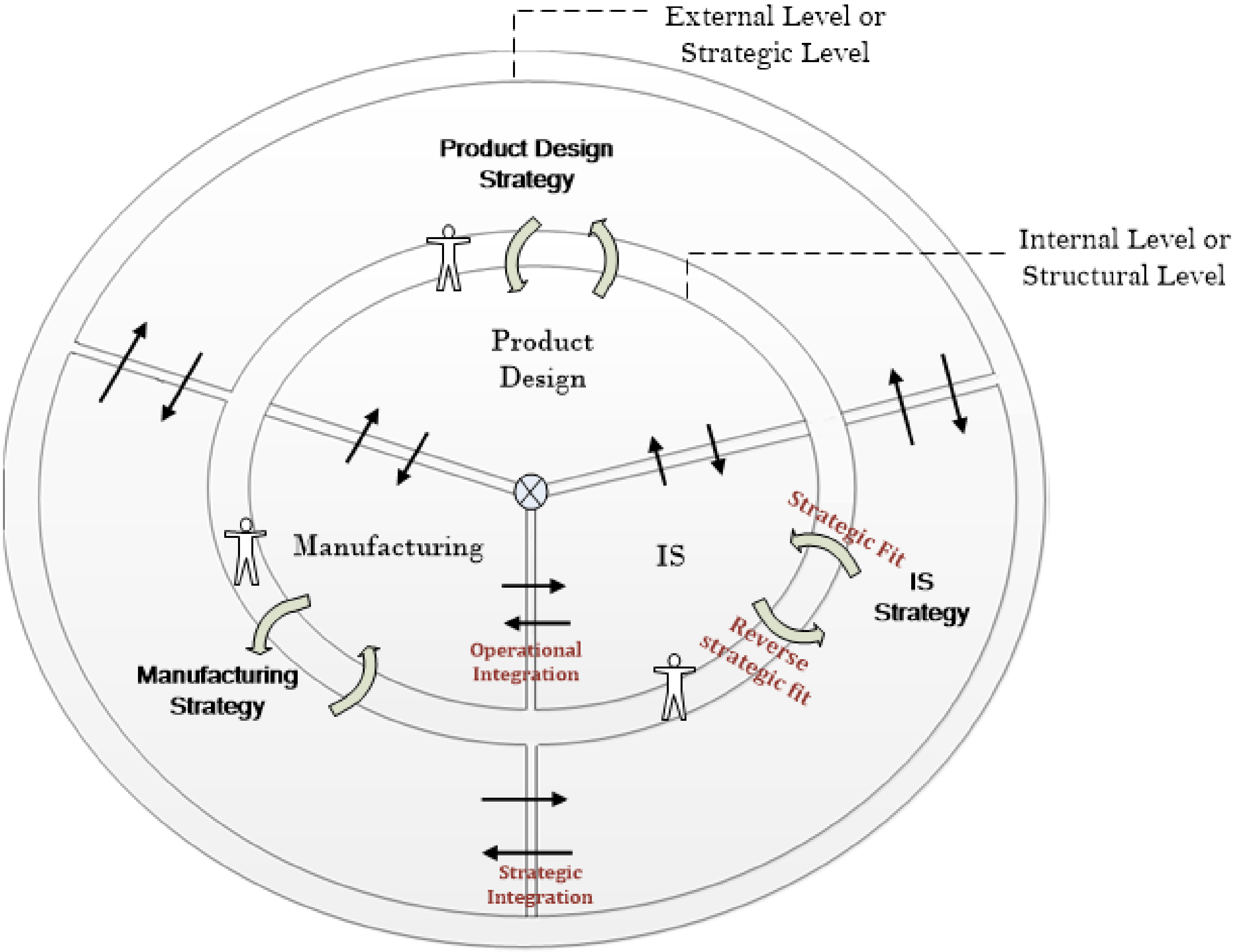


Figure 6. Co-evolution model with the different links between sub-domains

2 Links in the same domain at different levels: Strategic fit and Reverse Strategic Fit

We identify two types of links considering the direction of the relationship occurring within a given domain to relate its strategic (external) level and the internal (structural) level:

- The strategic fit, which has been at the centre of strategic management studies. This link highlight the need to align the firm with its external environment and in turn aligning the internal structure to be properly meshed with the strategy (Channon *et al.*, 2015). The strategic fit is acknowledge in the work of (Henderson et al., 1993) as the relationship enabling consistence between external and internal levels of the Business and Information Technology (IT) domains. It correspond to the traditional "top-down" approach that seeks to align the organisational processes and resources to the desired strategic capabilities (Slack & Lewis, 2002).

Based on this, three links can be defined relating the strategies of each of the domains (product, manufacturing, IS) to the design of each internal processes and resources.

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- The reverse strategic fit, which represents the same link performed in the opposite directions. The reverse strategic fit has been recognized in the work of (Goepp *et al.*, 2015). It is identified by the authors as a complementary type of alignment that may occur within the exploration of emerging sequences of alignment. Indeed, the reverse strategic fit implies the bottom-up relationship between external and internal levels where strategies are prompted by the internal capabilities or experiences coming from the operational level (Slack & Lewis, 2002). Similarly, to the former, three reverse strategic fit links are considered to relate each of the domains from the internal to the external level.

2.1 Product Design Strategic Fit and Reverse Strategic Fit

2.1.1 Product Design Strategic Fit

Product design strategic fit deals with the consistency between product design strategy and the product design itself.

Research has shown that the link between product design strategies and design processes focuses on the decisions leading to synthesize a design process that matches the product parameters and specifications (product lifespan, performance, quality, etc.) (Cross, 1989; Hsu, 2007). A design process is then structured through systematic techniques given by the selected design method (Cross, 1989). Strategic choices related to product design are mainly emphasized in form of design goals including: product features, current industrial standards, performance requirements or even environmental concerns. These design goals set out the limits and constraints of the design project down to the design team (Bloch, 1995). Designers work out a design proposal following settled goals which often leads them to make trade-offs between the functional demands (for example a non-porous surface) and customer's wishes (for example a range of colours relying on the material employed) (Cross, 1989). Moreover, when a product definition relies on a modular architecture, it might influence the approach of collaboration between designers. The communication should increase if they have to work on the same product module whereas less cooperation arises if the modules belong to different components that do not share interfaces (Harmel, Bonjour, & Dulmet, 2006).

Other impacts on the execution of the design processes might derive from the specifications of the product or product line related to its lifespan. Hence, strategic issues may result from product life cycle (PLC) information considered to provide guidelines for design process. For example, during the introduction phase of a product, a unique design would be targeted to attract attention in a crowded market. Later, uniqueness in design may be eclipsed by other criteria such as user friendliness or reliability. During the maturity phase of PLC, design may become again significant in repositioning efforts. Finally, in the decline phase, the offering of new products becomes an imperative. Designers must thus engage on activities for developing new products that may include new product lines, additions to existing product line, improvements and revisions to existing products, repositioning and cost reductions (Hsu, 2007).

Moreover, companies may rely on in-house development or rather on outsourcing when companies do not have enough personnel to dedicate to more fundamental research (Lupeanu, 2010). Outsourcing the decision making related to new product development and R&D processes is a strategic decision that has an impact on the extension and integration of internal assets, resources, capabilities and knowledge base. Boeing's decision to outsource the design of major aircraft sub-assemblies is a good example of the adaptive strategic response of the company to deal with unfamiliar technology domain. The company outsourced the domain where it has narrower capabilities focus than its competitors/suppliers. As a result, structural changes in the organisation were implemented in order to facilitate the collaboration of partners as well as to ensure they would adopt Boeing's working methods (Cantone, Testa, Hollensen, & Cantone, 2018).

Furthermore, for the adoption of IoT, corporations are repositioning their product strategy so that the value of data collected by sensors in IoT-enabled products will eventually overtake the value of the physical product itself (Goldense, 2019).

2.1.2 Product Design Reverse Strategic Fit

Product design reverse strategic fit represents the link from the internal level to the external level in the product design domain. In this link, decisions at internal level can be considered as the drivers of a change over strategic choices of the product domain

Especially in line with the procedures to deal with complex product design in evolutionary and uncertain contexts, small unplanned practices may contribute to shape strategic decision-making (Fathianathan & Panchal, 2009; Slack & Lewis, 2002).

For example, the designers of a firm can work out a way of 'modularising' the design so that one part of the product can be modified while the main structure of the product remains unchanged. A modular approach thus emerges from the company's experience namely the designer' experience and might become a strategic direction (Slack & Lewis, 2002).

Moreover, a further practical example described in (Koga & Aoyama, 2008) involves the setting up of a modular design approach that includes the lifecycle information of the product. As a result, an optimal design for the modular structure of the product family is generated that can potentially fits to market changes. This type of improvement in the design may become a driving force for a new direction towards sustainable design strategy allowing beating competition (Cross, 1989).

2.2 Manufacturing Strategic fit and Reverse Strategic Fit

2.2.1 Manufacturing Strategic Fit

The link between manufacturing strategy and the corresponding manufacturing system is acknowledged since long time with the work of (Hayes *et al.*, 1996 ; Hayes et al., 1984 ; Hill, 1987). The existence of this link has also been suggested by (Nemetz & Fry, 1988) and (Parthasarthy *et al.*, 1992)

One strategy for companies is to become broad differentiators focusing on manufacturing a variety of differentiated products. As a result, this category of companies set up intermittent batches to accommodate changes both in product mix and new product introductions fairly economically (Ward, 1996). For IBM, the shift from typewriters to electronic products impacted the layout of its facilities to satisfy the manufacturing of the new products. Greater automation was implemented as well as training for people to take on new responsibilities as 'owner-operators' of equipment areas in production lines (Swamidass, 2002).

Another example is the strategy of offshore outsourcing that implies the relocation of any part of a firm's value chain beyond national borders (Mohiuddin *et al.*, 2003). According to (Gorg *et al.*, 2004), offshore outsourcing leads to the restructuring of production in the industrialized countries towards more 'skill-intensive' or innovative activities. In addition, offshoring allows to develop strategic alliances where suppliers are considered as a source of resources enabling to consolidate the organisation' internal competencies.

2.2.2 Manufacturing Reverse Strategic Fit

The manufacturing reverse strategic fit concerns the way internal manufacturing processes may drive the definition of manufacturing strategies.

Consistent with this relationship, (Kim, Sting, & Loch, 2014) point out that bottom-up action plans usually begin as autonomous initiatives of lower-level managers. However, because of their limited power, these initiatives usually start small and are scaled up by earning top management's support. The reference from which autonomous initiatives becomes a top management's action plan lies on the extent of demonstrated value-generating potential. As illustrated by (Kim *et al.*, 2014), an autonomous initiative taken by two line managers consisted in physically dividing their production area into two sub-plants; one configured for high-volume products (large batch sized) and the second for low-volume products (small batch sizes). The result of these configurations was in the best interest of the company. The action derived on shorter delivery time for small-volume, nonstandard orders and the charge of a premium for faster delivery. Consequently, the initiative of segmentation of the production lines became on strategic action plan. It was implemented first on a single product type and later it impacts the whole design of the manufacturing area.

2.3 IS Strategic Fit and Reverse Strategic Fit

2.3.1 IS Strategic Fit

This link represents the association between a defined IS strategy which is implemented through decisions at the internal structure of the IS domain. The IS strategic fit is explicitly considered in the Technology Transformation Alignment Perspective in (Henderson et al., 1993). This is where the strategy depends on changes in technology which place the focus on aligning technology infrastructures. Thus, this link considers the application of the IT strategy related to the most adequate IT technologies, competencies and governance through the required configuration of IS architecture, processes and skills of IT personnel.

For example, the industrial sector integrates open source software as a part of its strategy of digitization. Other companies have decided an approach that combines open source with proprietary software. This strategic choice will entail changes in the IT infrastructure. Besides, significant organizational changes have to be made to install and run the software, as well as cost of training people and slow migration from previous systems. Another effect of this choice is that it fosters the development of more compatible and reliable solutions from suppliers (von Krogh *et al.*, 2007).

2.3.2 IS Reverse Strategic Fit

The IS reverse strategic fit represents the link between the internal infrastructure of IS and the IS strategy, where the former one can drive the definition of new IS strategies initiatives.

(Hsiao *et al.*, 1998) document the change of a strategy resulting from the introduction of a new database integration project. This project drives the need for the company to initiate a cultural change programme and readjust the defined processes and structure to align with the new technology. As a result, the current strategy of the company has to be redefined to support the structural changes realized. The authors note that this change was not deliberately planned but stimulated by the cited structural changes. In this way, as commented in their work, the strategy of a firm may be driven by changes in other elements rather than being a driver of them.

3 Links between different domains at the same level: Strategic Integration and Operational Integration

As for the strategic fit we rely on the work of (Henderson et al., 1993) to define the concept of functional integration. In the SAM, the functional integration is defined as the required integration between the business and IT domains. There are two kinds of integrations: the strategic one when the external level is considered and the operational one when it concerns the internal level. We extend this concept for the co-evolution of IS, product design and manufacturing. The following sections detail the notion of strategic and operational integration as well as the corresponding specific links in our model.

3.1 Strategic Integration

Strategic integration refers to the link that exists between business strategy and IT strategy (Henderson et al., 1993). Thus, the strategic integration reflects the interdependencies existing at external level. We use this notion to treat potential links that can be forged among strategies of product design, manufacturing and IS domains. According to this, there are six strategic integrations to consider.

3.1.1 Product Design-Manufacturing and Manufacturing-Product Design Strategic Integration

3.1.1.1 Product Design -Manufacturing Strategic Integration

The strategic integration between product design and manufacturing represents the potential correlation between the strategic decisions of product design and manufacturing strategy.

One approach that can show the influence from product design strategy to manufacturing strategy concerns the integration of geometric features into the same part to reduce the number of parts. The strategy of part integration results in more complex designs which lead to longer tooling lead times but can generate cost savings in production. Since the past three decades, the philosophy of making the product design easy to manufacture or focusing on reducing the total manufacturing cost is embraced within the approach of "Design for Manufacturing" (Ulrich *et al.*, 1993). More recently, companies have also focus on integrate sustainable features into the product design as a strategic decision. These new features require appropriate manufacturing process technologies like additive manufacturing. Top level managers should consider using the advantages of additive manufacturing (AM) – the industrial version of 3D printing- in terms of reduction of waste energy, thus creating added value for the user of their product (Frizziero *et al.*, 2017 ; Klahn *et al.*, 2015) .

3.1.1.2 Manufacturing-Product Design Strategic Integration

Regarding strategic integration between product design and manufacturing, the analysis of the link must be regarded from the opposite direction. Thus, this subsection considers the link going from manufacturing strategy to product design strategy.

Modularity-based manufacturing is a strategic choice that promises the combination of standardization and flexibility. The application of modularity principles in the manufacturing setting has foster the design of modular products to satisfy the customer needs (Tu *et al.*, 2004). Moreover, decisions on adopted process technology could impact product's characteristics such as size and shape, which subsequently influence product's performance. For example the process technology used for industrial diamonds creates crystals of varying shapes, and shape is a key determinant of the strength of the diamond as a distinctive feature in the market (Chen *et al.*, 2013). In this way, the output characteristics of a process technology can influence the product design strategy by impacting the product's features that became distinctive for the strategy of product differentiation.

3.1.2 Manufacturing-IS and IS-Manufacturing Strategic Integration

3.1.2.1 Manufacturing-IS Strategic Integration

The strategic integration between manufacturing and IS refers to the impact of manufacturing strategy on the strategic decisions related to IS.

For example, the increase of manufacturing flexibility relies on new technological developments that allows to adapt automation architectures of production systems from the MES to the ERP layer in which intelligent devices can be integrated and connected (Vogel-Heuser *et al.*, 2014).

Furthermore, novel applications could also be exploited to satisfy improvements concerning logistic competencies. Competitive plans for delivering orders are generally assured by ERP and other software. A company seeking to consolidate warehousing might focus on enabling collaborative platforms. As a result, the collaborative platform could exploit the use of Internet of Things (IoT) applications and associate RFID and ambient intelligence. This project would require re-designing the ERP to perform with new integrated devices and communicate in a collaborative environment (Reaidy *et al.*, 2014).

3.1.2.2 IS-Manufacturing Strategic Integration

This link represents the association between a defined IS strategy which can impact the strategic decisions of manufacturing. The impact of IS strategy to manufacturing strategy belongs to the classical example of competitive potential alignment perspective described in (Henderson et al., 1993). Within this perspective, competitive potential emphasizes the potential of strategic IS to generate new business opportunities. In this case we treat how IS can lead to new strategic paths in the domain of manufacturing.

The advent of big data and business analytics (BDBA) has enabled companies to create value. BDBA provides the basis to deploy agile organisation through timely and more accurate information about product demand and quickly design of integrated supply chain network, product, process and collaboration among partnering firms (Gunasekaran, Yusuf, Adelaye, & Papadopoulous, 2017).

3.1.3 Product Design-IS and IS-Product Design Strategic Integration

3.1.3.1 Product design -IS Strategic Integration

This link represents how the strategy of product design can have effects on strategic IS decisions.

This link can be demonstrated through the practice of co-creation as a new product design strategy in response to the trend of including customers into design projects for setting itself apart from competitors. Such decision will entail the development of IT capabilities including new strategic alliances in the IT domain. For example, the use of Business-to-Business platforms can supply the required system environment to fulfil such initiative (Jouny-Rivier, 2016).

3.1.3.2 IS-Product Design Strategic Integration

This link represents the association between a defined IS strategy which can impact the strategic decisions of the product design domain. The IS-Product design strategic integration also refers to the competitive potential alignment perspective described in (Henderson et al., 1993).

For example, Otis Elevator leveraged its information system to design a state-of-the art elevator that provides the highest level of service operations (Venkatraman, 2000). Another example can be related to leverage Product Data Management systems to integrate sustainability related data for added-value product design (Stark *et al.*, 2014).

3.2 Operational integration

With respect to internal sub-domains, we have interest also in the relationships at the structural level of product design, manufacturing and IS. This link has been called operational integration in the work of (Henderson et al., 1993) referring to the link between organizational infrastructure and processes and the IS infrastructure and processes. Thus, we borrow this term for co-evolution to designate the links among the three domains considering their internal decisions in terms of their respective processes and structures.

3.2.1 Product Design-Manufacturing and Manufacturing-Product design Operational Integration

3.2.1.1 Product design -Manufacturing Operational Integration

The product design-manufacturing operational integration link represents the relationship between product design processes and manufacturing operations.

Product-process integration is pursued in manufacturing plants so that manufacturing processes may incorporate a better understanding of product requirements and so that the product designer may incorporate manufacturing process capabilities into product specifications. One aspect that can be mentioned here are the activities related to product-process technology integration. These activities may include design for manufacturing analysis, formal design approvals or design and manufacturing job rotations (Swink, Narasimhan, & Wang, 2007).

For example, the case of a standard printed circuit board that has to be manufactured with a new environmentally friendly alternative. In this context, new features are introduced in the design which modifies the manufacturing process to be implemented. In this case, manufacturing engineers deploy a modular production executed by a reconfigurable manufacturing system (Puik, Gielen, Telgen, Van Moergestel, & Ceglarek, 2014).

3.2.1.2 Manufacturing-Product Design Operational Integration

The Manufacturing – Product design operational integration link associates internal decisions of manufacturing system which impact internal product design processes.

One example of the link between manufacturing and product design operations is described in (Pulakanam, 2011). This case considers the flawed manufacturing process of a new food product. Quality control procedures showed that a high rate of the manufactured products is rejected because of variations in weight specifications. After a thorough analysis where production staff was involved, they conclude that the design team failed to consider the process capability of the injector and the oven when determining the product weight specifications. Undertaking training on process capabilities will allow design staff to a well understanding of the product requirements and process capabilities (Pulakanam, 2011).

3.2.2 Manufacturing-IS and IS-Manufacturing Operational Integration

3.2.2.1 Manufacturing-IS Operational Integration

The manufacturing-IS operational integration link represents the relationship between manufacturing processes and IS internal processes and infrastructure. This operational integration is an example of the classical strategic execution perspective detailed in (Henderson et al., 1993)

In the semiconductor industry, the planning of Automated Transportation Systems (ATS) in the production plant requires integrated data system communication for equipment and systems in the factory. Since different interfaces can affect the implementation of ATS, a unified architecture should be planned to link the interfaces of MES, production equipment programs and ATS. As a result, IS managers could plan the design of innovative uni-interface technologies and applications to achieve the required integration (Chang *et al.*, 2016).

Moreover, statistical methods for prediction during production maintenance or for quality control need a considerable database to create reliable forecast. Thus, these production techniques should rely on effective exchange and sharing with respect to the implemented IT and data architecture (Schmitt *et al.*, 2016).

3.2.2.2 IS-Manufacturing Operational Integration

This manufacturing-IS operational integration link represents the relationship between IS internal processes and infrastructure and manufacturing processes. This operational integration is an example of the service level perspective detailed in (Henderson et al., 1993).

In this process the vision is that IT can improve internal processes of manufacturing by changing the accompanying IT infrastructure.

Theoretically, an ERP system collects and provides information, but it does not necessarily add value unless that information is exploited through further action. Focused on manufacturing, the impact of information would be mediated through the production resources namely the workforce involved in the manufactured product. Thus the usage of ERP system could enable the ability to plan and act by providing real-time information to operations as well as execution and planning functionality (Jamrose, 2017)

3.2.3 Product Design-IS and IS-Product Design Operational Integration

3.2.3.1 Product Design-IS Operational Integration

The product design-IS operational integration link represents the relationship between product design internal domain and IS processes and infrastructure. This operational integration is also an example of the classical strategic execution perspective detailed in (Henderson et al., 1993).

The adaptation of a product design approach or the deployment of learning methods for industrial designers by means of Information Technologies could be considered in this relationship. For example, in the work of (Frizziero, Francia, Giampiero, Liverani, & Caligiana, 2017) a dedicated software for TRIZ problem analysis is employed to assess the design of an open mould. The computer power of a PC optimizes the process by reducing the time of analysis when is made manually. (Song, Chen, Peng, Zhang, & Gu, 2017) describes an interactive system based on virtual reality technologies that provides customers a close-real experience of the product function. Then, the system records generated feedback for designers to improve the product. Thus, virtual technologies enable a learning environment where users can participate to design so that designers could make optimal choices for the product performance.

3.2.3.2 IS-Product Design Operational Integration

The IS-product design operational integration link represents the relationship between IS internal processes and infrastructure and product design processes. This operational integration is also an example of the service level perspective detailed in (Henderson et al., 1993).

In this perspective the vision is that IT can improve internal process by changing the accompanying IT infrastructure. For example, according to (Dinh, 2015), the integration of Knowledge Base Engineering (KBE) systems with CAD software allows design staff to create virtual product configurations with less time and effort that traditional design methods. This design approach reduces the need of user's level of CAD education since it captures and reuses engineering knowledge from the experts for less experienced designers.

4 Conclusion

The objective of this study aims at identifying the mutual links and underlying effects that can occur among the domains of our co-evolution model: the product design, the manufacturing and the IS domains.

Since our co-evolution model considers two levels for each domain, the external and the internal level, we have identified 9 potential links relating the six defined sub-domains. Based on strategic management literature as well as on research of strategic alignment, we have defined these links as belonging to two types: 1) the strategic fit and reverse strategic fit relating the same domain from external to internal level and vice versa and 2) the functional integration relating sub-domains at different level. Within the functional integration link, the links among external sub-domains correspond to strategic integration whereas the links among internal sub-domains correspond to operational integration. A third type of link concerning the links between different sub-domains at different levels i.e. manufacturing strategy linked to IS Infrastructure, has been neglected because this type of impacts does not fit with the hierarchical decision processes that companies have to adopt.

Therefore, this work focuses on investigating and describing these relationships. We draw on research to identify industrial events or cases that acknowledge each type of link. We exemplify them by describing the underlying impact generated.

Our work is thus positioned within the dynamic view of the proposed co-evolution model. In other words, we suggest that co-evolution is explained as the outcome of the dynamic interplay among these domains. We will further exploit this study to support the development of an approach as a part of our contribution aiming to manage co-evolution.

Chapter 5.

An Approach for model-based co-evolution management

1 Introduction

The last decade, important efforts have been made in the academic and industrial context to deal with challenges associated with future industrial systems. One major concern has been the development of international roadmaps mainly based around the FoF (Factories of the Future) in order to prepare the ground for the next generation manufacturing systems (Cardin *et al.*, 2017). A necessary step for enterprises to deal with this transformation is that they are capable to reinvent their business strategy in order to co-evolve with the environment. At the same time, the enterprises need to develop their internal competencies to ensure and fit to the evolution of environmental conditions (Eisenhardt *et al.*, 2000).

In this context, the contribution of this paper focuses on the co-evolution dynamic to help the transition of factories. As a result, we developed a modelling approach that aims to drive and manage the process of co-evolution in the industrial context. This approach is grounded on the coupling of 1) the static view of our proposed co-evolution model, represented by three domains and six sub-domains describing the strategic and structural components of each domain (See Chapter 3) and 2) the dynamic view concerning the potential links (See Chapter 4).

Therefore, our approach consists in a set of steps that exploits both described views of our co-evolution model. The process of co-evolution is cyclic by nature and hence, the co-evolutionary dynamics among domains describe naturally a continual process of reciprocal effects. Our approach of co-evolution builds a dynamic path of sequences to define a co-evolution path or trajectory. In other words, the path that the enterprise should follow in order to achieve a desired state (TO-BE).

Thus, the resulting approach consists in three phases (see Figure 7). These phases are detailed in the following sections.

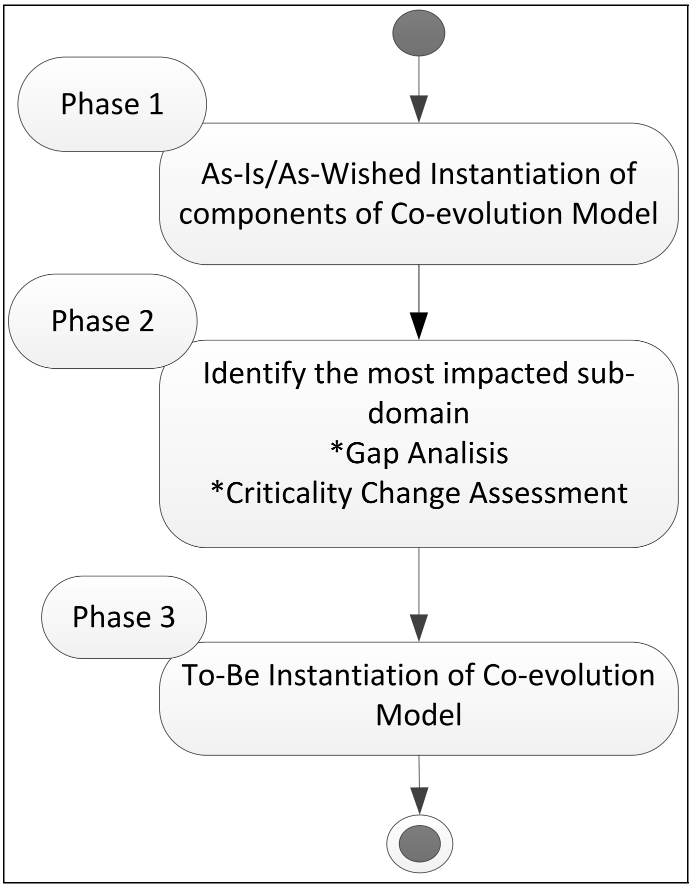


Figure 7. Synthetic view of three phases of the co-evolution management approach

2 Co-evolution Management Approach

In this section we detail the three phases that constitute the approach to carry out and manage co-evolution.

2.1 Phase 1. AS-IS/AS-WISHED co-evolution model instantiation

The first stage of our approach consists in working out the AS-IS and AS-WISHED specific co-evolution models. In other words, the co-evolution model presented in Chapter 3 is instantiated for a given company at different times on the evolution axis.

The AS-IS model corresponds to the current state and the AS-WISHED to the desired state that the enterprise wishes to implement. Thus, both models are separated each other by a certain interval of time within the evolution axis.

Instantiation requires analysts to gather for a time T (AS-IS situation) as well as for a time T+1 (AS-WISHED situation) the data related to the 18 components of the co-evolution model. In other words, the static view of the co-evolution model serves as a guide to structure AS-IS and As-whished analysis. In this context, the components that are not instantiated are considered as not relevant for the considered project. However, at least one component of each sub-domain has to be instantiated because, in view of co-evolution, all the sub-domains have to be taken into account simultaneously.

In order to instantiate the co-evolution model, the choice of a specific modelling language has to be made in adequacy with the nature of the 18 components of our co-evolution model. According the analysis, we made in Chapter 3, we distinguish the external (or strategic) level from the internal (or structural) level:

- *For the external level,* which consists of the set of decisions made at strategic level we propose to use natural language. Therefore, the analysis of existing and desired situations should provide elements to specify strategic decisions and map them to the decisions detailed within each component: scope, governance and competencies. Refer to Table 7 in Chapter 3 for the complete detail of decisions-based modelling for strategic sub-domains.

For the internal level, which consists of the set of decisions made at structural level, we propose to exploit enterprise modelling. The analysis of the existing and desired situation should provide elements to specify structural components at the moment of instantiation. In chapter 3, the constructs of enterprise modelling ISO 19440 (2007) have been mapped to the structural components of each sub-domain (see Table 8). On this basis, the modelling formalism fitting to each component can be chosen. The Table 9 sums up the formalisms used to represent each component of the co-evolution model.

The processes components of each domain can be represented using BPMN (Business Process Modelling and Notation) process diagram (OMG, 2013). This diagram is chosen because it provides graphical elements and detailed semantic to represent business process operations that are easily understood by business analysts and stakeholders. In addition, BPMN is a standard notation widely supported and expressive enough for the aforementioned modelling purpose.

Moreover, within the basic modelling constructs of BPMN process diagrams we also use lane and pool. We exploit the lane construct to indirectly represent the skills components of each domain. Indeed, the lane construct allows to represent the roles of a participant within the pool to which it belongs and can therefore be associated to the skills required to perform the task of the modelled process. Moreover, the pool represents a participant in a process so it is useful to represent the organizational structure of product design domain.

Regarding the infrastructure components, different formalism is chosen depending on the domain. The IS infrastructure component, it can be represented using UML (Unified Modelling Language) deployment diagram (OMG, 2017). UML is chosen because it is a widespread standard modelling language that covers the construction of static and dynamic views of software systems by the use of different diagrams. We exploit the UML deployment diagram which enable to represent the computational resources and so the IS infrastructure by using modelling elements like nodes and components.

The manufacturing infrastructure & support processes component can be represented using SysML block definition diagram (BBD) (OMG, 2006). SysML is chosen because it reuses ULM concepts and augments them to support the modelling of a broad range of systems including facilities. The taxonomy of SysML diagrams including the ‘block’ seems suitable since they can represent any level of the system hierarchy including physical/mechatronic components (Hause, 2006). In this view, it fits to our modelling concern. Additionally, like UML, SysML provides platform-independent graphical languages so they can be used with any compatible drawing tool (Basi *et al.*, 2011).

Component of the co-evolution model	**Proposed formalism**
Product design Processes Manufacturing & support processes IS processes	BPMN process diagram
Manufacturing skills IS skills Product design skills	Lane in BPMN process diagram
IS architecture	UML deployment diagram
Manufacturing infrastructure & equipment	SysML Block Definition Diagram (BBD)
Product design structure	Pool in BPMN process diagram

Table 9. Components of co-evolution model and proposed modelling formalisms

The activity diagram of the phase 1 of the co-evolution approach is represented in the Figure 8.

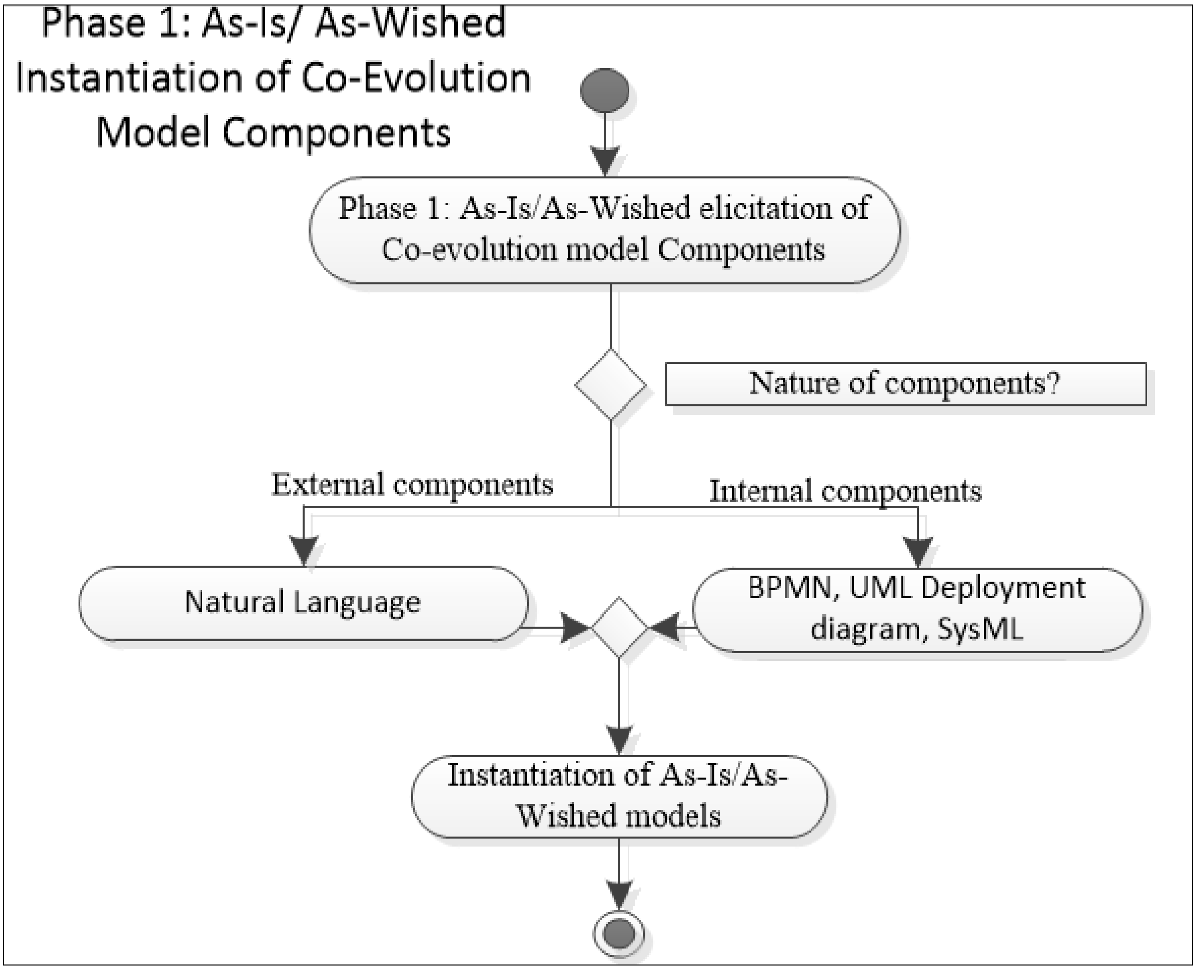


Figure 8. Activity diagram detail of the phase 1 of the co-evolution approach

2.2 Phase 2. Identification of the most impacted sub-domain

Once the AS-IS and AS-WISHED models obtained, the TO-BE model has to be carried out progressively. The TO-BE model corresponds to the state of the company that will be effectively implemented. It is a feasible As-Whished state that takes into account the co-evolution constraints from the AS-IS state.

As a preliminary phase, the phase 2 of our approach aims at identifying the most impacted sub-domain. By doing this, we are able to consider a starting point allowing to define the critical links or interactions that need to be managed.

To succeed in, we propose a two-step work (gap identification and change criticality evaluation). The first step consists in a comparison activity between the AS-IS and AS-WISHED models in order to identify main gaps between the same components of each model.

These gaps will allow us, during the second step, to identify the most impacted sub-domain through change criticality assessment.

2.2.1 Gap identification

The gap identification step consists in comparing the models that we have instantiated for the AS-IS and AS-WISHED states. In this way, we are able to identify three types of components and related gaps if any:

i) The components that are instantiated in the AS-IS model and not instantiated in the AS-WISHED model. These are not taken into account as we have explained previously.

ii) The components that are instantiated in the AS-WISHED model and not instantiated in the AS-IS model. For these components we have to instantiate the AS-IS state in order to define if there is a gap between these components.

iii) The components that are instantiated in both models. For these components we have to identify if a gap exists or not.

2.2.2 Criticality change assessment

Once the list of components that have to evolve set-up, we quantify the gaps as follows:

i) For each component, we define if the change is incremental or disruptive:

- Incremental changes are understood as occasional, usually pre-planned upgrades that trigger the cumulative development of innovations following previously established trajectories (Schweisfurth *et al.*, 2011).
- Disruptive changes are understood as those which lead to a major divergence from established trajectories, also sometimes referred to as path-breaking innovations (Christensen *et al.*, 2010).

ii) Then, we evaluate the change criticality of each sub-domain. This is defined as the sum of the change criticality of each component belonging to each sub-domain. The change criticality is ranked as follows: 0 for a component that does not evolve, 1 for a component with an incremental change, and 5 for a component with a disruptive change.

iii) At last, the most impacted sub-domain is the sub-domain with the highest change criticality.

The activity diagram of the Figure 9 details the described steps to carry out the phase 2.

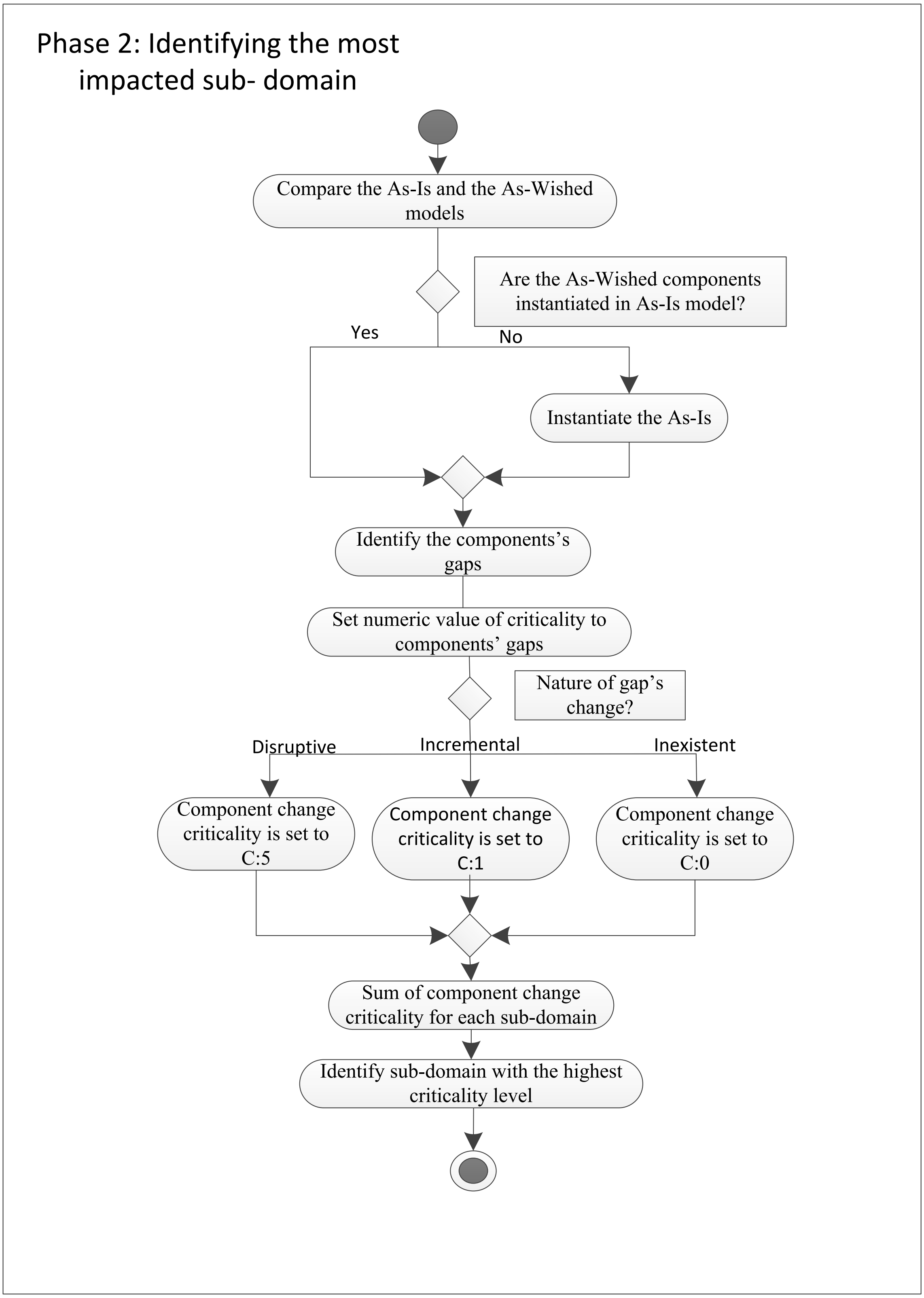


Figure 9. Activity diagram detail of the phase 2 of the co-evolution approach

2.3 Phase 3. TO-BE Model set-up

In this section we progressively work out the model of TO-BE state. We propose an iterative process based on the following principles:

2.3.1 TO-BE Set-up Principles

We consider the AS-IS and AS-WISHED models and relate them to the feasibility and the co-evolution constraints. Indeed, the instantiation process is iterative by nature requiring to involve at each step the stakeholders needs in order to satisfy everyone's' expectations.

Likewise, feasibility constraints have to be taken into account during each step of the TO-BE model set-up phase. One useful tool for this purpose can be the cost-analysis benefit (Bause *et al.*, 2014). These constraints can be related to:

a) technical/operational constraints, which are linked to the technical resources that establishes that the option under study can operate in the desired manner (i.e. existing technical expertise, rigidity of the existing infrastructure);

b) Financial constraints, upon which the company determines the financial risk of the project (i.e. a technology that is too costly to implement).

c) Time constraints linked to the human efforts required.

The co-evolution constraints are treated in a given order enabling to setup progressively each component of the TO-BE model. The most impacted sub-domain is used as a starting point. Then, considering strategic fit as the backbone of co-evolution, we consider *strategic fit – reverse strategic fit* depending on the level of the most impacted sub-domain. Then, the functional integrations at the same level than the most impacted sub-domain are considered.

2.3.2 Set-up TO-BE Iterative Process

The iterative process we propose exploits phase 2 and the fact that strategic fit has to be considered before functional integration. It consists of the following steps:

i) First, we set-up the TO-BE model of the components of the most impacted sub-domain by taking into account the feasibility constraints of these components.

ii) Then we set-up the TO-BE model of the components of the other level of the most impacted sub-domain enabling to consider the co-evolution constraints related to the strategic fit or reverse strategic fit.

iii) Then, we set-up the TO-BE model of the components of the other two sub-domains at the same level than the most impacted sub-domain enabling to consider the co-evolution constraints linked to functional integrations.

iv) Then, we set up the TO-BE model of the components of the other level of the domain instantiated in the previous step enabling to consider the co-evolutions constraints linked to strategic fit or reverse strategic fit in these domains.

v) Finally, we adjust the TO-BE model considering the remaining functional integrations links that have not been taking into account yet.

3 Illustration: Using the Modelling-based co-evolution management approach for an industrial project

In this section we propose to illustrate how the proposed approach is deployed using information of an industrial company. The approach will need to be further validated but this will be addressed in the section of perspectives related to this work research.

3.1 Context of the industrial project

This project concerns a company which is specialised in the design and manufacturing of automated handling equipment and special systems for the industries producing wood-based panels and other flat materials.

The scope of the operations offered by the company includes consulting, technical engineering, production, assembly, installation and commissioning of PLC controlled production lines and complex material flow systems, in particular: cooling and stacking lines, automatic storage systems, sanding and cut-to-size lines, packing lines, material flow automation, special lines, material handling and packing lines for steel industries.

The main customers of the company are the industries from the wood and steel sectors. The company headquarter is located in France and employs 20 people. They also have one division in Germany and one automation division also in France.

Additionally, they propose solutions to their customers regarding the installation, the implementation, the monitoring and the commissioning of the production line.

- During the upstream phases, the company plans and engineers the production lines that fit to the customer demand in order to satisfy their specific production requirements and facilities.

- The installation and commissioning phases consist of the assembly and electrical wiring of the installed modules on the customer site as well as the programming of the PLC that control the production line. The installation and commissioning phases take 2 months.

The set of enterprise activities performed by the company to be competitive encompasses two main phases as shown in the Figure 10.

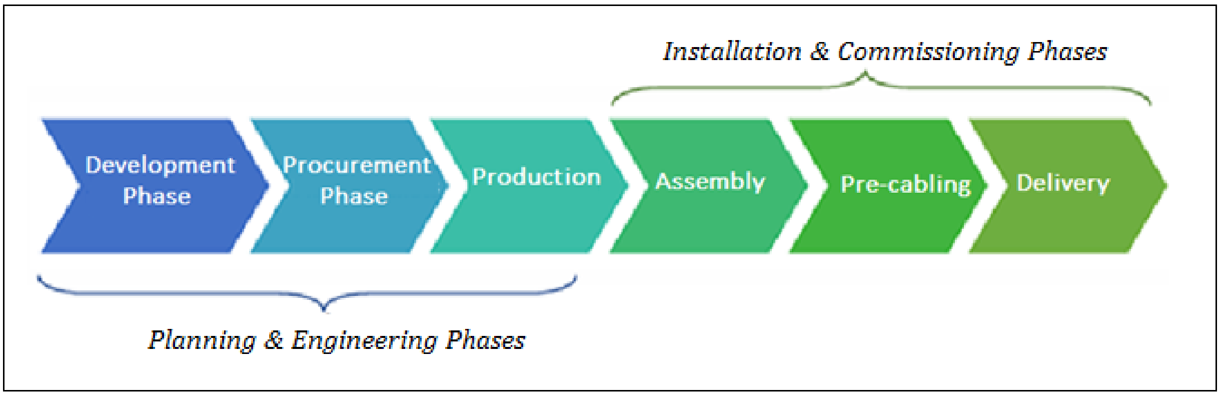


Figure 10. The value chain of the company under study.

In the Table 10 we list the main modules that compose an automated production line.

1.	Front Belt Conveyor	7.	Gantry strapping
2.	Pile-Turner	8.	Chain Conveyor
3.	Trough Chain Conveyor	9.	Chain Conveyor with harrows
4.	Transfer Carriage	10.	Foil wrapping machine
5.	Chain Conveyor	11.	Chain Conveyor
6.	Cross strapping machine	12.	Trough Chain Conveyor
7.	Dunnage Handling	13.	Central Controller

Table 10. List of main modules composing an automated production line

The company aims to gain a competitive advantage particularly to face its German competitors which have better control on sawing machines and focus on mechanical engineering. Therefore, the manager seeks a significant reduction in time during installation and commissioning phases of the production lines. As a result, fewer resources would need to be allocated (i.e. human resources) on the customer site. To this end, the company envisions to make evolve their products by faster test and configuration when installing the production line. In this way, they aim to tackle the effort and time required to put the production line into service. This will allow the company to ensure competitiveness by providing new functionalities in order to fulfil future manufacturing needs. Moreover, the maintenance performed for the products is expected to be optimized in the future time.

We based on this industrial example to illustrate our co-evolution management approach in the following sub-sections.

3.2 The exploitation of the co-evolution management approach

3.2.1 Phase 1. AS-IS/AS-WISHED co-evolution model instantiation

This phase aims to set-up the AS-IS and AS-WISHED model. We first identify the relevant components of the co-evolution model at different time periods related to the existing and the future contexts of the firm under study. Then, we instantiate the components using the modelling formalisms that we propose enabling to instantiate external and internal components of the co-evolution model.

We present the information gathered about the existing context and the future context of the company as follows:

<u>Existing situation (AS-IS):</u>

- The automated machines that the company manufactures currently rely on a centralized product architecture based on traditional PLC (Programmable Logic Controller). The commissioning process of the product in the customer factory takes 2 months. During this time, technical staff is required to make journeys to the customer site to ensure the installation and the commissioning for the correct operation of the automated production line. The staff is qualified to modify existing equipment items as required through the setting up of the full automated lines

- The product control architecture consists of a central electrical cabinet which includes the following automation components: the PLC controller, I/O cards, security-related items, the amplifiers supplying voltage to the motors and the contactors. Currently, some I/O cards components have started to be distributed into the modules. Besides there exist other electrical cabinets containing amplifiers, I/O cards and in some cases a controller connected to higher complex modules as in the case of the foil wrapping machine. More recently, the company has decided to introduce distributed I/O cards with no need to be embedded into the electric cabinet. However, the positioning of these elements differs from line to line.
- The products (machines) manufactured by the company are basically the same for each of their customers. Currently, the company has decided to leverage the alliance formed with an electrotechnical industry to develop supervision software in order to offer preventive maintenance within the production lines.

Desired situation (AS-WISHED):

- The automated machines that the company will manufacture will rely on ‘Plug and produce’ technologies. The concept ‘Plug and Produce’ or ‘Plug and Work’ describes an architecture enabling to decrease the configuration and programming efforts during commissioning steps. The commissioning process of the product will be significantly reduced.
- The new product architecture will be decentralized. Each module will be a standalone unit with an embedded electrical cabinet including their own PLC controller, amplifiers, and I/O cards. As a result, this architecture will enable easier integration of modules. Indeed, the modules will enable to be tested separately. Besides, the architecture will allow the possibly to carry out some activities of commissioning like the electrical wiring and testing prior to the on-site installation in the customer site.
- The machines would be connected to a Plug and Work server. This networking interface will bring about distinctive product functionalities like:

  a) Effort of PLC programming that tends to zero,

b) Feedback functionality used for predictive maintenance,

c) Faster installation time since modules can be configured easily and/or tested previously in the plant and

e) The development of predictive maintenance. Related to this latter aspect, it is desired to optimize the provided supervision software in order to support the monitoring of machine conditions in real-time.

Instantiation of the AS-IS and AS-WISHED Components for the Industrial Case:

Based on the previous information, we instantiate the components identified for the AS-IS and the AS-WISHED states as shown in the Figure 11 and the Figure 12.

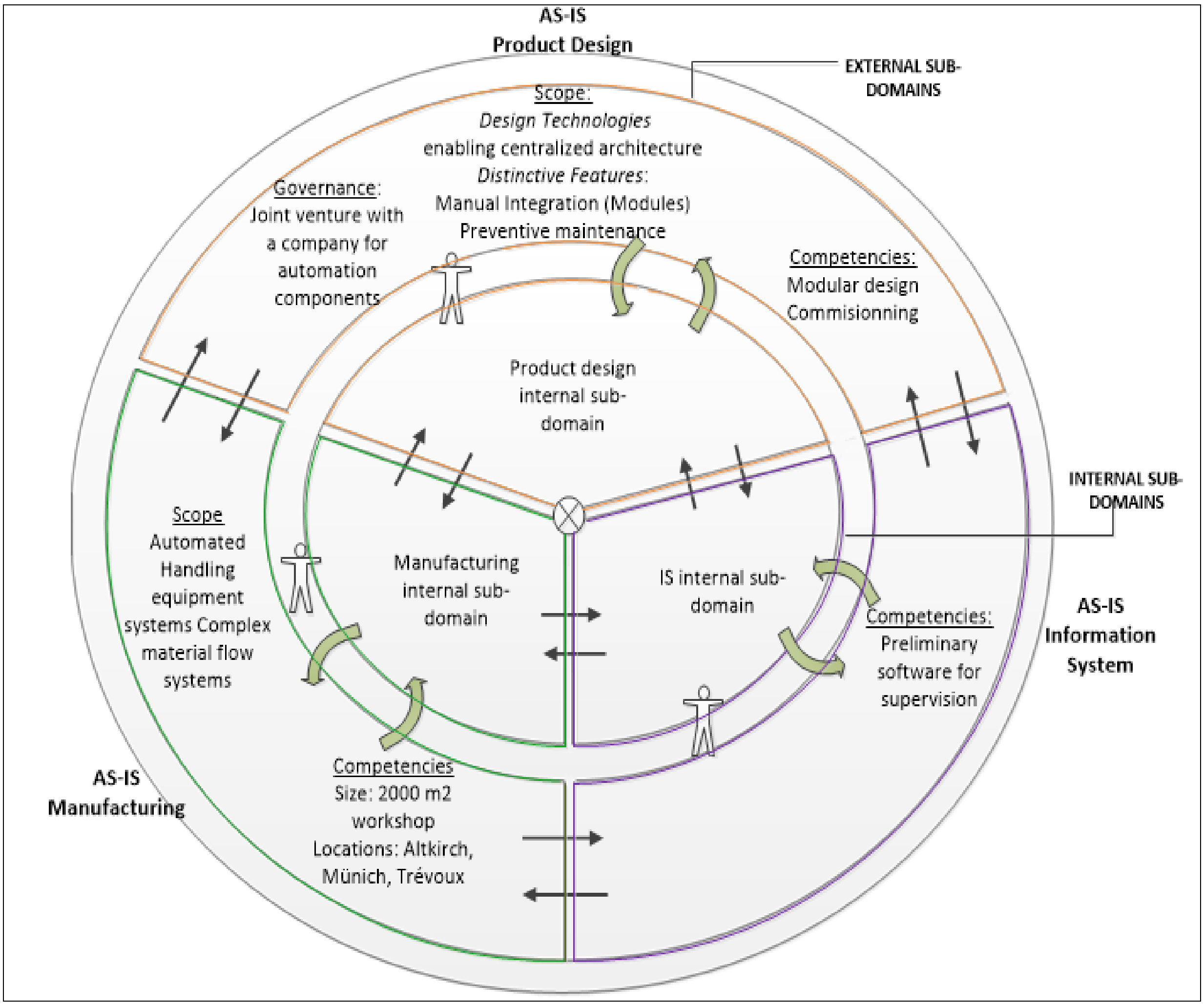


Figure 11. AS-IS external components instantiation of co-evolution model

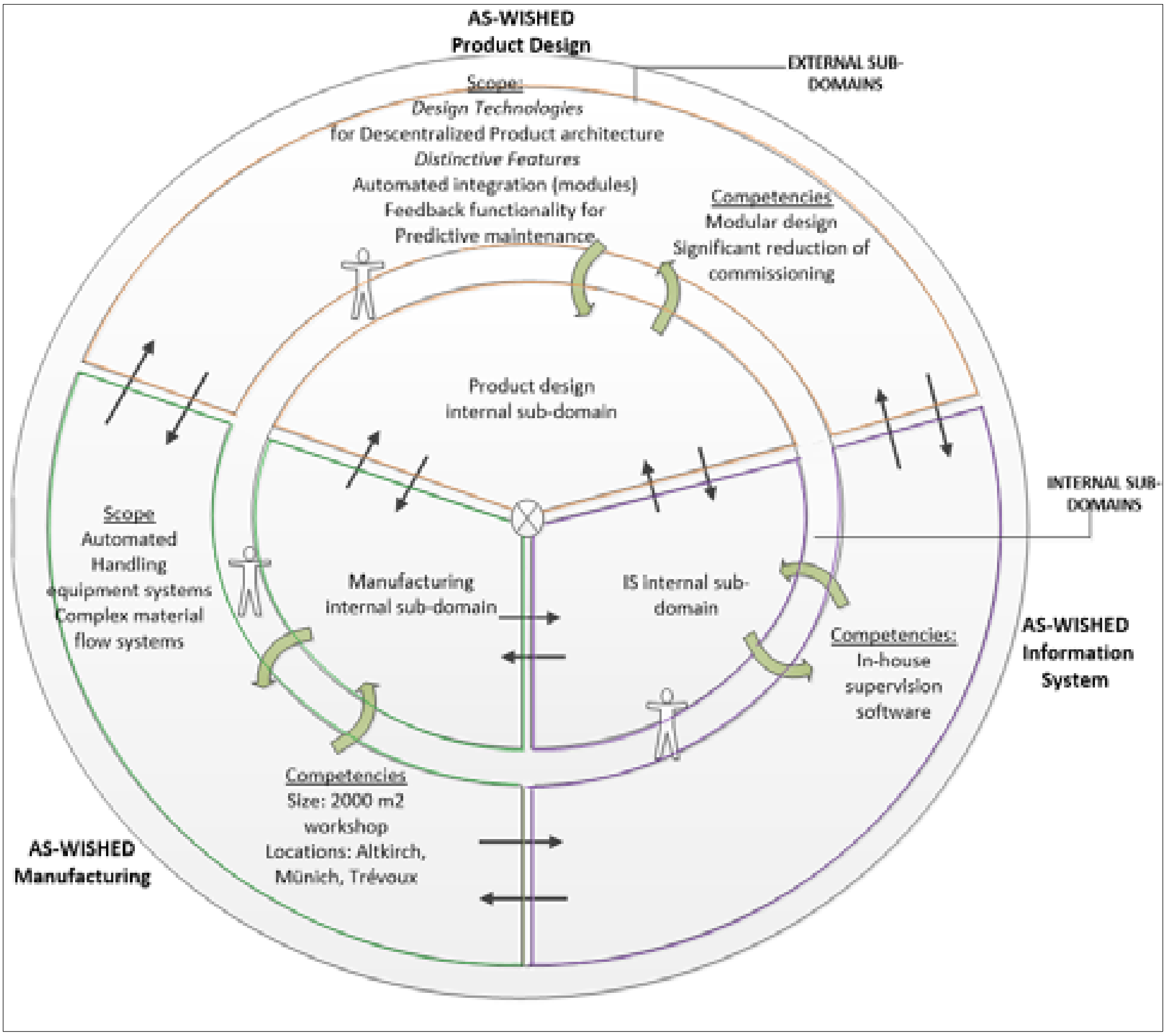


Figure 12. AS-WISHED external components instantiation of co-evolution model

Concerning the internal components, we can instantiate the internal product design sub-domain regarding the current product control architecture and the desired one. The Figure 13 and the Figure 14 illustrate the UML deployment diagrams that instantiate AS-IS and AS-WISHED product architectures.

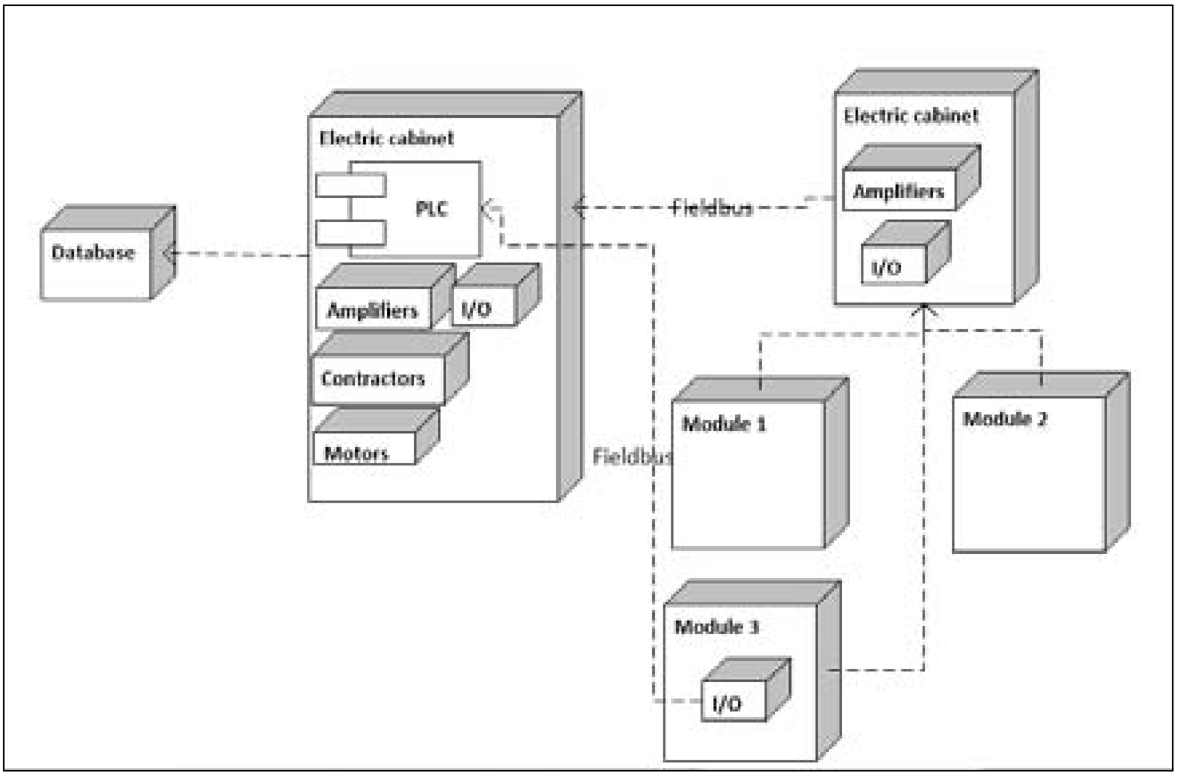


Figure 13. AS-IS product control architecture

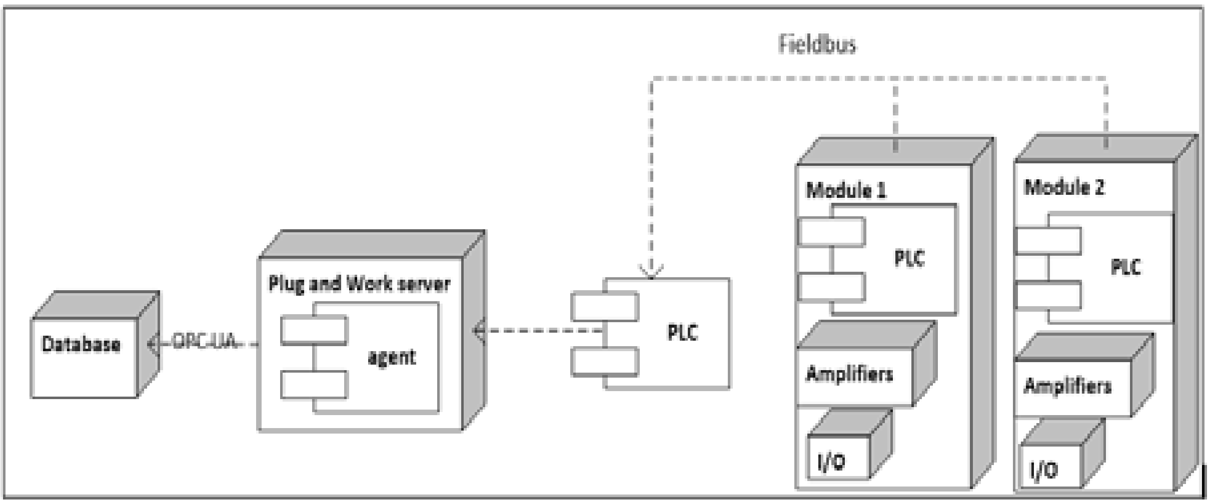


Figure 14. AS-WISHED product control architecture

3.2.2 Phase 2. Identifying the most impacted sub-domain

After the instantiation, the following phase consists on identifying the most impacted sub-domain. By identifying the most impacted sub-domain, we consider this sub-domain as the starting point from which critical links take place. These critical links define the co-evolution path underlying the mutual impacts among subdomains that has to be managed over time.

To identify the most-impacted sub-domain, two activities have to be performed: the gap identification and the change criticality evaluation. We carry out these steps in the defined order as follows:

3.2.2.1 Gap Identification

The gap identification step consists of comparing the instantiated AS-IS and AS-WISHED models and identify if components exist or not in the both models as it is required to further identify the nature of gap (change). This can be done in the form of a checklist as shown in Table 11.

Instantiated Components	**AS-IS**	**AS-WISHED**
Product Design Strategy		
Product Design Scope		
• Design Technologies	X	X
• Distinctive features	X	X
Product Design Governance		
• Partnership for Design	X	?
Product Design Competencies	X	X
Manufacturing Strategy		
Manufacturing Scope	X	X
Manufacturing Governance		
Manufacturing Competencies	X	X
IS Strategy		
IS Scope		
IS Governance		
IS Competencies		

Table 11. Checklist of components comparing between the AS-IS and AS-WISHED models.

After the comparison task, three types of components and related gaps can be found:

i) The components that are instantiated in the AS-IS model and not instantiated in the AS-WISHED model. As we can observe in the checklist above, the component Partnership for design is only instantiated in the AS-IS model but not in the AS-WISHED model. This component is related to an existing joint venture with a company that provide electric and automation services to the manufacturer company. Therefore, this component is not relevant since it has not been instantiated in the AS-WISHED. As a result, the component is not taken into account.

ii) The components that are instantiated in the AS-WISHED model and not instantiated in the AS-IS model.

    There are no components in this category.

i) The components that are instantiated in both models. For these components we have to identify if a gap exists or not.

    The components instantiated in both models are the components of product design sub-domain and the components of the manufacturing sub-domain.

At this point, we present the list of components completed by crossing the components that have been instantiated and thus considered relevant for the co-evolution project as shown in Table 12.

Instantiated Components	**AS-IS**	**AS-WISHED**
Product Design Strategy		
Product Design Scope		
Design Technologies	X	X
Distinctive features	X	X
Product Design Competencies	X	X
Manufacturing Strategy		
Manufacturing Scope	X	X
Manufacturing Governance	/	/
Manufacturing Competencies	X	X
IS Strategy		
IS Scope	/	/
IS Governance	/	/
IS Competencies	/	/

Table 12. List completed with the instantiated components

3.2.2.2 Criticality change assessment

The next step aims to evaluate the change criticality for each sub-domain. This is done by identifying first the components' gap. We set a numeric value according to the type of change identified in the gap. Three types of changes will be evaluated as defined before:

1) Inexistent change, meaning that component does not evolve. For this change, the criticality value is set to 0.
2) Incremental change, meaning that the component will evolve gradually following pre-planned trajectories of change within the corresponding sub-domain. For this change, the criticality value is set to 1.
3) Disruptive change, meaning that the component will evolve in a radical way involving a path-breaking innovation within the corresponding sub-domain. For this change, the criticality value is set to 5.

In this case, we show in the Table 13 the list of components. For the relevant components that were instantiated, we mark the corresponding type of change related to the components' gaps between the AS-IS model and the AS-WISHED model.

			Type of Change			
Instantiated Components	**AS-IS**	**AS-WISHED**	**Disruptive**	**Incremental**	**Inexistent**	**Value**
Product Design Strategy						
Product Design Scope						
Design Technologies	X	X	X			5
Distinctive features	X	X		X		5
Product Design Governance	/	/				
Product Design Competencies	X	X	X			5
Manufacturing Strategy						
Manufacturing Scope	X	X			X	0
Manufacturing Governance	/	/			/	
Manufacturing Competencies	X	X			X	0
IS Strategy						
IS Scope	/	/			/	
IS Governance	/	/			/	
IS Competencies	/	/			/	

Table 13. Identification and Evaluation of Gaps for each instantiated Component.

Therefore, in this case, we identify in the Table 14 the existing gaps concerning the instantiated components related to the product design external sub-domain.

Component	**Sub-Domain concerned**	**Gap Identified**
Scope Component	Product design External Sub-domain	Design Technologies The gap concerns the need to integrate new technologies (i.e. plug and produce technologies) enabling to shift from existing centralized product architecture to a future decentralized product architecture. This change represents a paradigm shift (disruptive change) that will simplify considerably the installation, wiring, configuration and system integration. Distinctive Features This gap concerns the added functionalities of the product in the future time related to: • the integration of modules and the feedback functionality linked the level of product maintenance enabled. These features are associated to the shifting of the existing product architecture and the new product technologies that should be integrated to achieve this objective. It would represent a disruptive change for the product.
Design Competences Component	Product design External Sub-Domain	This gap concerns the tasks related to the commissioning of product. These tasks will be simplified and the time reduced some of them allowed to be prior executed in the manufacturer company which will impact the time and effort required to put the production line in service. This change linked to the disruptive shift of the product control architecture, so it is considered as disruptive.

Table 14. Description of gaps identified between the instantiated components of the illustration case.

Since there are no relevant gaps for the other sub-domains, the most-impacted domain is the Product external sub-domain with a total change criticality of 15.

3.2.3 Phase 3. TO-BE Model Set-up

The phase 3 regards the set-up of the TO-BE model in a progressive way. The TO-BE model will allow to define the sub-domain's co-evolution path towards a feasible state that will be effectively implemented by the company

Thus, we consider the evolution-related information of the components derived from the AS-IS and the AS-WISHED models and we create the instances of the TO-BE model by relating these components to the *feasibility* constraints and *co-evolution* constraints. The stakeholder's needs must be also considered for the evaluation of TO-BE model's alternatives.

According to Phase 2, the Product external sub-domain is considered as the starting point to identify the critical links that should give rise to the co-evolution path (cf. Figure 15).

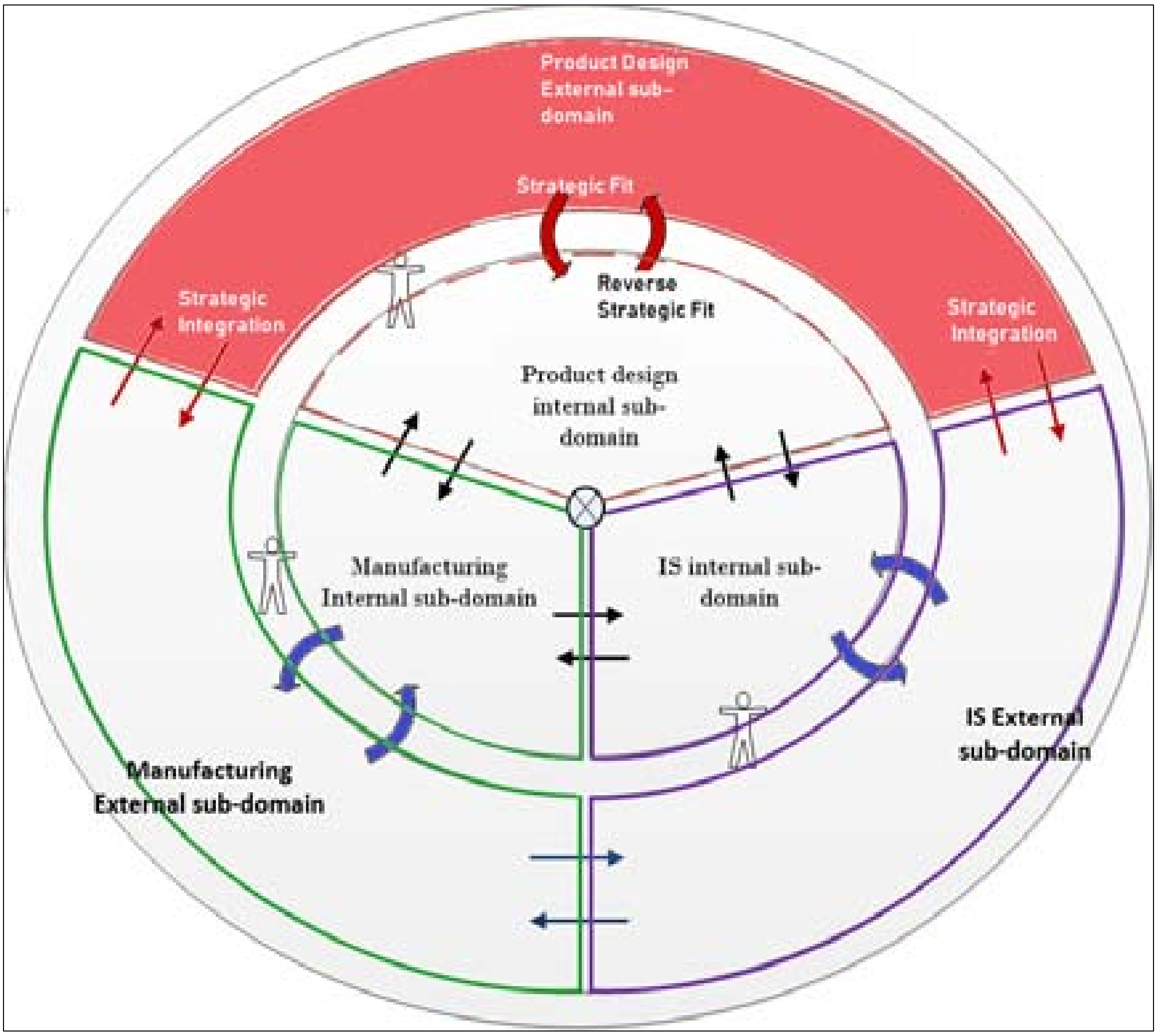


Figure 15. Product design external sub-domain as a starting point of co-evolution path

3.2.3.1 TO-BE set-up: step 1

The construction of the TO-BE model is initiated by the instantiation of the components of the most impacted sub-domain which is, in our case, the Product design external sub-domain.

For this step, we consider the instantiated components from the AS-IS and AS-WISHED models. In addition, we have to consider feasibility constraints related to technical/operational requirements related to the components that need to be matched as well as financial constraints or time constraints related to the need of the company. The description of the instantiated components for the product design external and internal sub-domain is presented as follows:

-*Product Scope*: the objective of this component is to set up the choices regarding the adoption of specific design technologies that will enable to reconfigure the existing product control architecture. The choices of new integrated technologies to support the change of product control architecture have to be done. Furthermore, the specificities related to the maintenance policy linked to the enabled feedback functionality of the product architecture are provided. In this case, the analysis of feasibility constraints allows to determine design alternatives relying on the choice of automation technologies that will support the shift towards more decentralized product architecture. These choices have to be evaluated according to related feasibility constraints. (cf. Table 15).

-*Product Governance*: the objective of this component is to address the choices related to partnerships for design. For example, the company might choose to rely on the joint venture that already exists with another company or create other alliances to contract electric and automation services. Furthermore, related to design policies, the company deals with the objective of reducing the commissioning time

-*Product Competencies*: the objective of this component is to define the choices in the design of products that will allow to gain a competitive advantage against its competitors. In this case, the competitive advantages rely on the previous explained components mainly related to the changes in the product control architecture allowing to reduce the commissioning time to a minimum.

The Figure 16 presents a schema to illustrate this initial TO-BE set up step for the case under analysis.

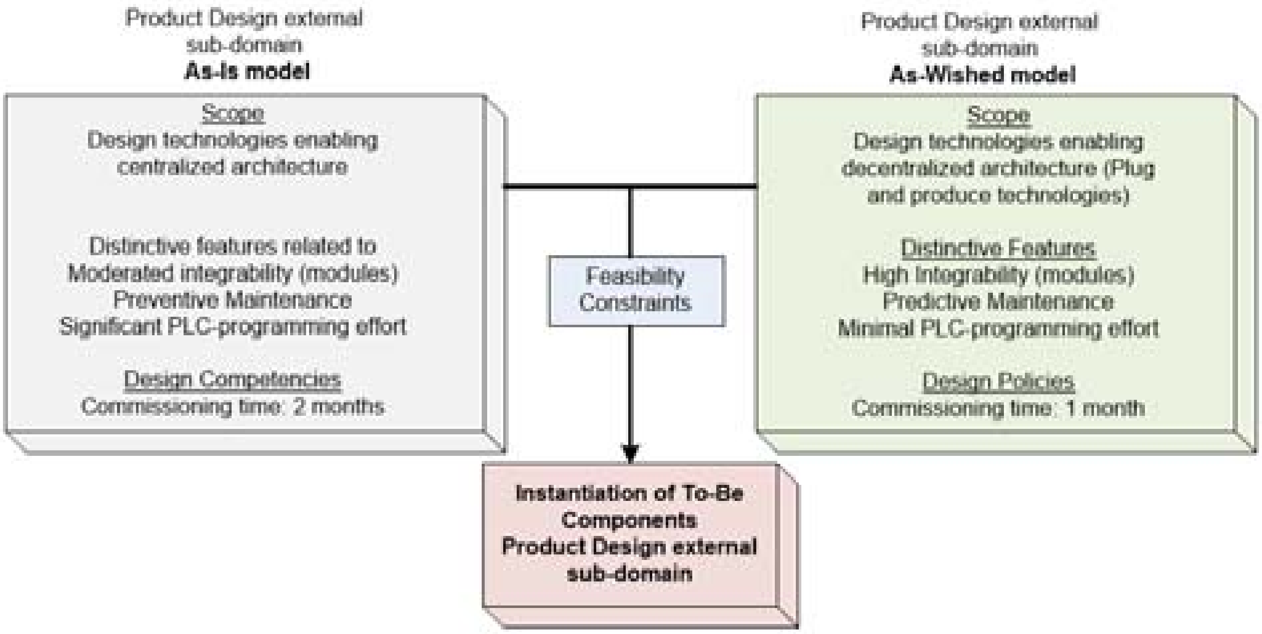


Figure 16. Scheme of the TO-BE set up process of the Product design external sub-domain

In the Table 15 we show some feasibility constraints that can be considered linked to the product scope component and the product design competencies component that we have instantiated.

Product design external sub-domain		Feasible Constraints	
AS-IS Components	AS-WISHED Components	Requirements – Technical / Operational Constraints	Financial/Time Constraints
A1: Product Scope Design technologies enabling centralized product control architecture	A1: Product Scope Design technologies for decentralized product control architecture	Power rating compatible with the voltage level Coarse granularity (plug in and out of modules) Mechanic/Pneumatic control Compatible data exchange protocols Interface requirements Storage requirements Security requirements	Estimated Costs Cost of devices Cost of technologies (i.e. plug and produce technologies) Cost of Personnel Cost of allocated resources Cost of data communications Time Schedule Testing time
A2: Product Scope Preventive Maintenance (manual)	A2: Product Scope Predictive Maintenance (based on sensor monitoring)	Measurement devices Measurement baseline Maintenance actors Material resources Informational resources Maintenance management	
A3: Design Competencies Commissioning time set to 2 months	A3: Design Competencies Commissioning time set to 1 month	Criticality of commissioning activities Installation steps that cannot be eliminated	

Table 15. Possible feasible constraints concerned for the TO-BE set up of Product Design external sub-domain.

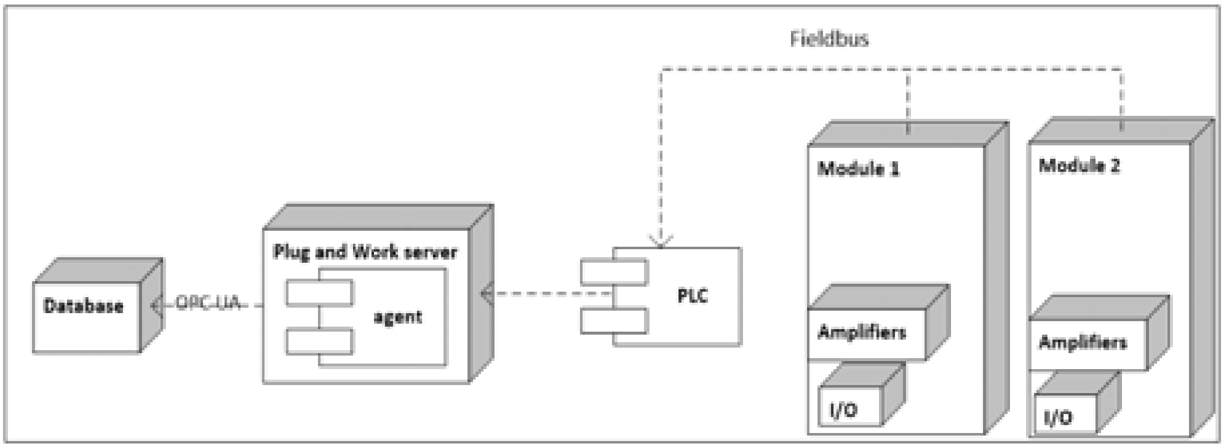
3.2.3.2 TO-BE set-up: step 2

The aim of this step is to set up the TO-BE components of the other level of the most impacted sub-domain. This is to say the components of the product design internal sub-domain. This is done by considering the co-evolution constraints related to the strategic fit which is the first link to be considered.

For this aim, feasibility constraints concerning this internal sub-domain have to be also considered. The description of the instantiation of product design internal components is done as follows:

-*Structure of design unit*: The objective of this component is to choose the organizational structure of the product design unite. In this analysis, this component is not concerned by the changes of the product strategy

-*Product Design Processes*: The adaptation of design processes is required to allocate the changes of the product strategy. These changes mainly correspond to the shift to a more decentralized architecture enabled by automation technologies. In this case, the analysis of feasibility constraints allows to determine design alternatives relying on the choice of automation technologies the desired shift. In our case, two main alternatives are proposed: 1) a product architecture with distributed automation elements (amplifiers and I/O cards) for each module (see Figure 17) a product architecture with distributed PLC and automation elements (amplifiers and I/O cards for each module) like the AS-WISHED product architecture (cf. Figure 14) . Furthermore, the specificities related to the maintenance function are set up. In this case, the main alternative proposes to deal with sensor-based maintenance enabling to monitor pre-defined variables of temperature and vibration for motors and bearings In addition, the changes related to allocation of sensors into the machines for predictive maintenance have to be considered into the design solution approaches.



-Skills of design: The skills of design team need to co-evolve to match the engineering requirements of the strategic choice related to the new product control architecture and the integration of technologies.

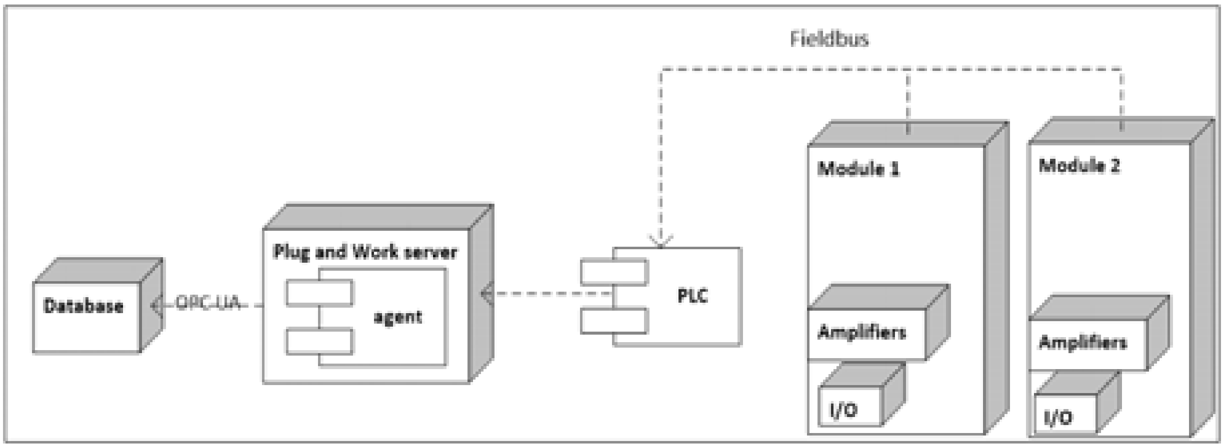


Figure 17. Product control architecture alternative with decentralized automation components

3.2.3.3 TO-BE set-up: step 3

The aim of this step is to set-up the TO-BE components of the sub-domains located at the same level than the most impacted sub-domain (product design external) meaning: the manufacturing external sub-domain and the IS external sub-domain.

This is done by considering the co-evolution constraints related to the functional integration link which is the second critical link to be considered.

For this aim, feasibility constraints concerning these external sub-domains have to be also considered.

The description of the instantiation of manufacturing design external components is done as follows:

-*Manufacturing scope*: The objective of this component is to define the production technologies that will support the product strategy. For example, the company under study might choose to increase the level of standardization of the manufactured machines and their automation components or the integration of automated workstations in the production plant to deal with the features of the new control architecture of the product.

-Manufacturing Governance: The objective of this component is to define the choices related to partnerships to support the manufacturing of the automated machines and handling systems. For example, the company has to decide if the development of sensors for the maintenance function will be purchased or will be developed internally. The same choice is linked to the adopted product technologies integrated in the new control architecture. This decision is often associated with the level of technical competencies that the company aims to develop for the future objectives.

-Manufacturing Competencies: The objective of this component is to define the competencies that the manufacturing system requires in order to implement the variations of the product control architecture. For example, the company might need to redefine the plant layout to accommodate the requested changes in the production system.

Concerning the IS external sub-domain, the component involved regard the *IS Competencies* enabling the company to develop the applications software to deliver predictive maintenance.

3.2.3.4 TO-BE set-up: step 4

The aim of this step is to set-up the TO-BE components of the other level of the sub-domains that we have previously addressed in the step 3.
In the step 3, we have addressed the TO-BE models of the manufacturing external sub-domain and the IS external sub-domain. Therefore, the internal level of the manufacturing and IS domain are concerned.
This is done by considering the co-evolution constraints related to the strategic fit link.
For this aim, feasibility constraints concerning these internal-domains have to be also considered.

The description of the instantiation of manufacturing design internal components is done as follows:

> *-Manufacturing infrastructure and equipment:* The objective of this component is to define the specific technical configuration for the production processes that will support the former manufacturing strategic integration with product design strategy. For example, the choice of special purpose machines, the modification of production

scheduling or the required adjustments that have to be done in the configuration of production equipment are considered in this component. Technical constraints will play a role in these settings.

-Manufacturing Processes and Support Processes: The objective of this component is to define the choices related to the production process and support processes that will support the requested changes in the product. For example, the choice of alternative operations sequences to handle the production of specific machine pieces having sensors aiming to deploy maintenance function.

-Manufacturing Skills: The objective of this component is to define the skills required for the production team to handle the changes or evolutions linked to the mentioned production operations.

Concerning the internal IS sub-domain, the main implications are derived from the increased competencies impacting the level of skills of IS technical staff to improve developed applications in terms of maintenance. For example, the company might need employees with a skills profile allowing them to handle the new applications as well as the evolving technological infrastructure and process that support them.

3.2.3.5 To-Be set-up: step 5

The aim of this step is to adjust the TO-BE model so far constructed by considering the remaining functional integrations links that have not been taking into account yet.
In our case, these functional integrations links concern the adjustments made mainly between the product design and the manufacturing domain at internal level. For example, the identified variations from the production processes have to be communicated to the product design unit in order to make suitable updates to the product design methods. The Figure 18 shows the circular schema representing the instantiated To-Be co-evolution model.

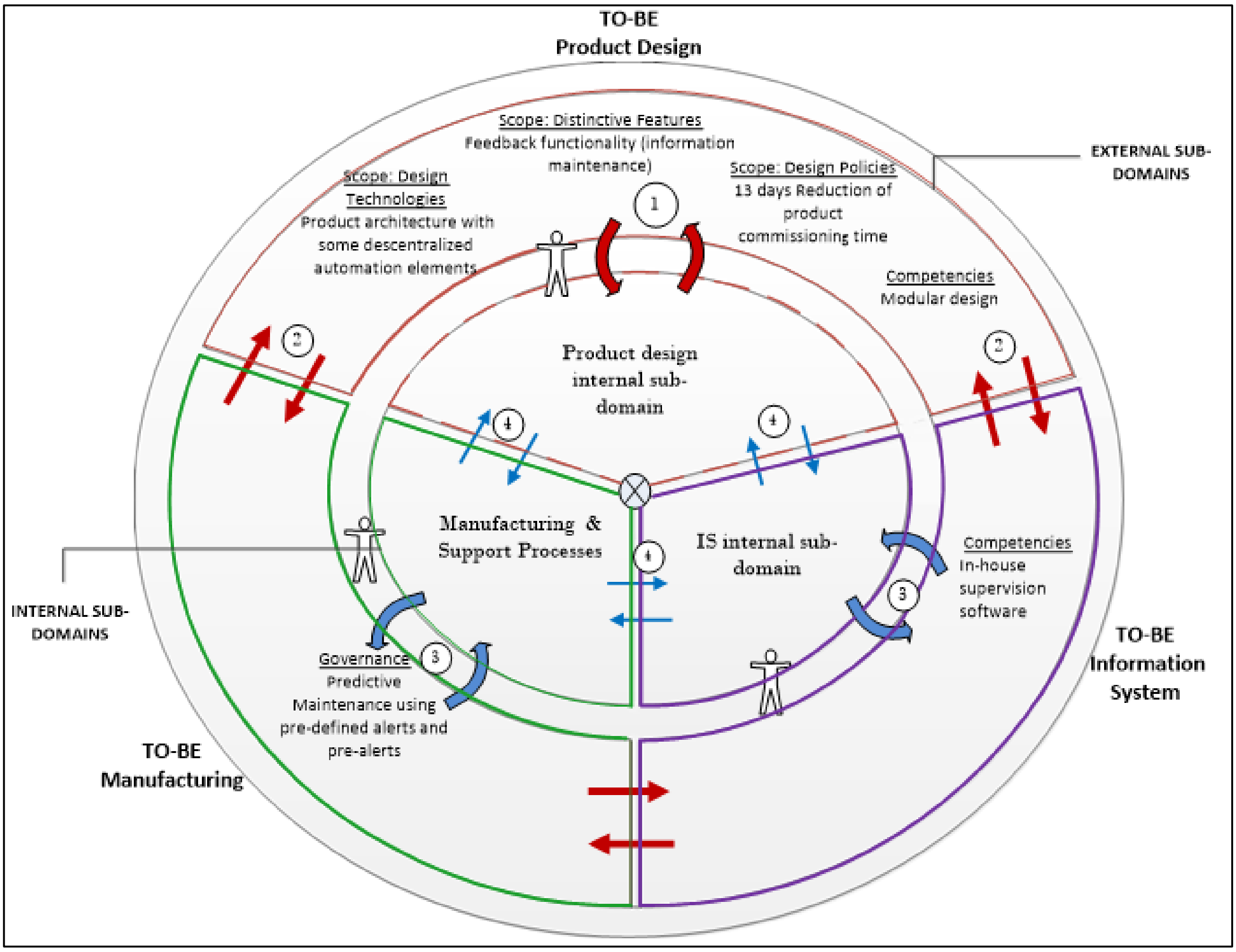


Figure 18. General schema of the instantiated To-Be co-evolution model

4 Conclusion

In this chapter, we have focused on a co-evolution management approach and its illustration aiming to provide a global view of the proposed co-evolution management approach. The considered components are not exhaustive, but it is representative of a transition scenario of an industrial company that produces automated handling systems for automated production lines.

The industrial example has a main focus on making evolve the product design external sub-domain by introducing ‘plug and produce’ control architecture. This architecture would allow a significant reduction of the commissioning time supporting competitive advantage against German competitors. The standard commissioning time handled in the present situation is of 2 months. The analysis of the components in the AS-WISHED state leads to derive a TO-BE scenario that considers changes of lower impact than the components of the envisioned AS-WISHED state.

Thus, the TO-BE state concerns the distributed implementation of automation elements like the amplifiers and the I/O cards for each of the modules. This allows to pre-deploy some tests and electrical wiring in the factory shop reducing the installation time spent in the customer site. As a result, this product architecture allows a final reduction of 13 days.

The difference of the implemented architecture between the AS-WISHED and TO-BE states is mainly due to the gap related to technical skills from the involved staff to deal with PLC programming and predictive maintenance conditions. The company needs to make evolve the competencies and skills required to adopt more radical changes.

This is a crucial example of co-evolution where the evolutions at strategic level require making a fit by making evolve the current competencies and skills of human resources. Co-evolution requirements are made explicit through the analysed impacts and constraints involved when addressing co-evolution links.

Based on this, we consider that our proposed approach of co-evolution is interesting to help manage the synergies and interdependencies of the different components along the temporal dimension. Regarding the implementation of more radical changes, CPS-based technologies have been considered for the transition linked to the relevant communication capabilities commonly associated to these systems. However, the developments in this field create higher expectations within industrials, even though recurrent limitations are often associated to the high investments to be made for their adoption.

In the proposed approach, we have pointed out the consideration of technical and economic constraints through the instantiation process of the TO-BE model. Related to CPS approaches, the decision shows that the communication condition reached for the predictive maintenance in the TO-BE state allows achieving the second level of CPS condition in a five-level scale of CPS conditions according to the functions provided by the CPS. This condition can be seen as a first step that will allow the preparation of the enterprise conditions at higher and lower levels, (i.e. staff training) in order to achieve solutions closer to the envisioned AS-WISHED state.

Chapter 6. General Conclusion

This dissertation takes place in the context of Fof, SF and I4.0, in which companies tend to evolve to remain competitive. The focus of this work is on supporting companies to manage this transition. The scientific contributions are multifold:

- First, we clarify the FoF, SF and I4.0 concepts and highlight their differences and complementarities.
- Second, we make a full state of the art of the implementation and engineering approaches to give a big picture of the researches in the FoF, SF, and I4.0. It shows that IS and human force role are crucial.
- Third, we propose an enhanced co-evolution model with a static and a dynamic view. It is the base to manage the transition from the AS-IS to the TO-BE state.
- At last, the model is completed with an operational co-evolution management approach that exploits the co-evolution model and is based on a set of rules (criticality change assessment, feasibility constraints, strategic fit as first co-evolution link).

The insights obtained from the illustration of our approach enables us to question now about the issues upon which our research work could be strengthened. Therefore, we present here the main limits that we find out related to our contributions:

- Although the proposed co-evolution approach is illustrated, a validation is of the approach is necessary. As a first observation, the instantiation of the models without a computer based tool remains time-consuming.

- The proposed approach enables the iterative instantiation of the components of the co-evolution model for different time frames. This allows to globally identify decisions to be taken according to the defined content of components. Some of these components are related to the integration of technologies. As such, the approach enables to identify the technological gap when analysing the gaps between components. However, the support to help in the choice of technologies should be enriched.

- One of the development axes that could be better exploited in the co-evolution model concerns the industrial sustainability practices. The consideration of environmental impacts in the co-evolution could be integrated.

Considering the limits observed in our contributions, the associated perspectives derived are:

- The evaluation of the efficiency of the proposed approach through an empirical industrial deployment.

- Second, the development of a software that can support the automatic application the co-evolution management approach by enabling the introduction and modification of component information to handle the modelling of components' alternatives for the generation of co-evolution paths.

- Last but not least, the proposal of a decision making tool to help the selection of the relevant new technologies to be implemented according to an instantiated co-evolution TO-BE state and the evaluation of their environmental impacts.

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Publications

- **National Conferences without proceedings:**

i. Marti Nieto F de A.. "Factory of the Future: which Integration Approaches?" presented to Journée STP de GDR MACS 2016, 3-4 November, Colmar, France.
ii. Marti de Nieto F. "Adequate Research Directions for Smart Factory: A literature survey", presented at JD MACS session during the IFAC World Congress 2017 (session), the 20th World Congress of International Federation of Automatic Control, 9-4 July, Toulouse, France.

- **International Conferences with proceedings:**

iii. Marti Nieto F. de A., Goepp V., Caillaud E. "From Factory of the Future to Future of the Factory: Integration Approaches" published in the proceedings of the IFAC World Congress 2017, the 20th World Congress of International Federation of Automatic Control, 9-4 July Toulouse, France

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iv. Marti Nieto F., Goepp V., Caillaud E."Factory of the Future: An Enhanced Co-evolution Model for Mastering Industrial Transformation", accepted to the IEEE SMC 2019, the IEEE Conference on Systems, Man and Cybernetics, October, Bari, Italy.

Résumé

Dans le contexte actuel, la transformation de l'outil industriel par l'intermédiaire de nouveaux paradigmes de performance tels qu'Usine du Futur (Factory of the Future FoF), Industry 4.0 (I4.0) ou encore Smart Factory (SF) est au cœur des préoccupations actuelles des industriels. Les travaux présentés dans cette thèse portent sur la problématique de passage d'une situation spécifique existante (AS-IS) vers une situation cible type Usine du Futur (TO-BE) en prenant en compte la situation souhaitée AS-WISHED et les contraintes de ressources. Dans ce cadre, la principale contribution porte sur une approche reposant sur un modèle de co-évolution permettant de guider ce projet de transition au sein de l'organisation. Sur la base des travaux de Tolio et al. (2010), nous avons proposé un modèle de co-évolution amélioré en intégrant le niveau stratégique, le rôle du système d'information (SI) et celui de la place l'homme. Sur le plan théorique, le nouveau modèle de co-evolution aborde 3 domaines Produit/Production/SI qui sont structurés en deux niveaux d'analyse : externe (stratégique) et interne (structurel). L'ensemble de 6 sous-domaines comportent chacun 3 composants couvrant les choix relatifs à chaque sous-domaine et niveau d'analyse. Sur le plan managérial, la gestion de la co-évolution réside dans la modélisation des ces composants. Ensuite, nous caractérisons des liens de co-évolution existants entre les différents sous-domaines du modèle de co-évolution proposé. La démarche d'exploitation du modèle de co-évolution comporte trois étapes et considère les contraintes opérationnelles et les contraintes dites de co-évolution liées à la gestion des liens ou impacts entrant en jeu dans la co-évolution. Il permet de passer progressivement des modèles AS-IS et AS-WISHED pour aboutir à un modèle TO-BE.

Mot clés : Transformation de l'industrie, Usine du Future, Industry 4.0, Smart Factory, Approche basée modèle, modèles AS-IS AS-WISHED TO-BE, Gestion de la co-évolution, Système d'Information, Modélisation d'Entreprise.

Abstract

Within the current context, the transformation of industries through new paradigms of performance such as The Factory of the Future (FoF), Industry 4.0 (I 4.0) or even The Smart Factory (SF) is at the heart of the industrials' current concerns. The present work address the problem of the transition from a specific situation (AS-IS) to a target situation alike FoF (TO-BE) considering the desired situation AS-WISHED and the resources constraints. In this line of action, the main contribution concerns an approach based on a co-evolution model enabling to guide manufacturing industries to perform such a transition. Based on the work of Tolio et al. (2010), we propose an enhanced co-evolution model that integrates the strategic level of decisions, the information system role (IS) and the role of the human workforce. From the theoretical perspective, this new model consists in 3 domains: Product design/ Manufacturing/ IS which are structured into two levels of analysis: external (strategic) and internal (operational). The resulting structure of 6 sub-domains is in turn composed of 3 components covering the decisions related to each sub-domain and level of analysis. From the management perspective, the management of co-evolution relies on the modelling of their components. Hence, we exploit the modelling language constructs of the ISO 19440 (2007) standard for the internal components. Then, we characterize the existing co-evolution links between the different sub-domains of the proposed co-evolution model. At last, a 3 phase approach enabling to exploit the enhanced co-evolution model is proposed. It considers the feasibility constraints and the co-evolution constraints linked to the management of the links or impacts that came into play in the co-evolution. As such, it enables to work out progressively a feasible TO-BE model.

Keywords : Transformation of the industry, Factory of the Future, Industry 4.0, Smart Factory, Model-based approach, AS-IS AS-WISHED TO-BE model, Co-evolution Management, Information System, Enterprise Modelling