Sede Amministrativa: Università degli Studi di Padova

Dipartimento di Tecnica e Gestione dei Sistemi Industriali, DTG Vicenza

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DOTTORATO DI RICERCA IN INGEGNERIA MECCATRONICA E DELL'INNOVAZIONE MECCANICA DEL PRODOTTO

INDIRIZZO IMPIANTI INDUSTRIALI E LOGISTICA

CICLO XXXII

Reconfigurability Principles in the Design and Management of Advanced Production Systems

Integrazione di principi di riconfigurabilità nella progettazione e gestione di sistemi di produzione avanzati

Tesi redatta con il contributo finanziario della Fondazione Cassa di Risparmio di Padova e Rovigo

Coordinatore: Chiar.ma Prof.ssa Daria Battini, Ph.D.

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ABSTRACT

In the last years, production companies are facing radical changes forcing to improve their standard in product and process design and management. High flexibility, dynamic market demand, increasing customization, high-quality products, flexible batches and short product life cycles are among the key factors affecting the modern industrial and market context and characterizing the emerging Industry 4.0 era.

These trends inevitably affect both the production strategy to adopt and the production system design. From the production strategy viewpoint, industrial companies attempt to meet every customers' request and satisfy their individual needs. For these reasons, they are switching from Make-to-Stock (MTS) and Make-to-Order (MTO) strategies to Delay Product Differentiation (DPD). DPD is a hybrid strategy that strives to reconcile the dual needs of high-variety and quick response time, by using the concept of product platforms, defined as a set of sub-systems and interfaces that form a common structure from which a stream of derivative product variants can be efficiently produced and developed. A large number of industrial companies introduced product platforms as tool to reach the benefits of DPD, e.g. Sony, for the development of the Walkman, Kodak, Black & Decker and Hewlett-Packard are relevant applications. From the production system viewpoint, traditional manufacturing systems i.e. Dedicated Manufacturing Systems (DMSs), Flexible Manufacturing Systems (FMSs) and Cellular Manufacturing Systems (CMSs), show increasing limits in adapting to the most recent market features. Such systems can be effectively used to mass-produce product platforms but advanced manufacturing solutions are needed to produce the remaining components necessary to reconfigure the product platforms into the final variants (Huang et al., 2019). In the last few years, Next Generation Manufacturing Systems (NGMSs), i.e. Reconfigurable Manufacturing Systems (RMSs) and Reconfigurable Assembly Systems (RASs), rise to respond to the dynamic market changes. This is achieved by designing both the system and the machines for adjustable structure in response to the dynamic market demand and to the introduction of new products.

Aim of this dissertation is to proposing innovative methods, models and tools aided at including the emerging principles of reconfigurability in designing products and advanced production systems, i.e. manufacturing and assembly, to improve the overall performances of the industrial plants. The

achievement of these goals is driven not only by a direct interest of modern industrial companies, but also by the strong commitment of a great number of research councils located in many areas of the world through funding projects. Within the context of European projects, relevant examples are the EU-funded projects *'Rapid reconfiguration of flexible production systems through capability-based adaptation, auto-configuration and integrated tools for production planning'* promoted in 2015, *'Skill-based propagation of plug-and produce devices in reconfigurable manufacturing systems'* and *'Adaptive automation in assembly for blue collar workers satisfaction in evolvable context'* promoted in 2016.

The research activity is developed according to a research framework, which highlights three main research areas: (1) design of modular product platforms, (2) design of reconfigurable manufacturing systems and (3) design of reconfigurable assembly systems. Each chapter of this dissertation is devoted to a specific area of the defined research framework and, after revising the main literature and identifying the research trends, illustrates the research activities as well as the main results and findings. The explored research topics lead to theoretical, methodological and practical contributions of help to support real-world industrial companies in facing modern emerging trends.

SOMMARIO

Negli ultimi anni, le aziende produttive stanno affrontando cambiamenti radicali, come la richiesta di elevati livelli di personalizzazione e flessibilità, i quali hanno, inevitabilmente, un impatto significativo sulla scelta della strategia produttiva da adottare nonché sulla progettazione dei processi produttivi stessi. Per quanto riguarda la strategia produttiva, le realtà industriali stanno superando le strategie produttive comunemente adottate come il Make-to-Stock (MTS) e il Make-to-Order (MTO) a favore di strategie più evolute come il Delay Product Differentiation (DPD). Il DPD è una strategia ibrida volta a riconciliare la duplice necessità di elevata varietà di prodotti e rapido tempo di risposta ai clienti, introducendo il concetto di piattaforma di prodotto, definita come un insieme di sotto-sistemi ed interfacce che formano una struttura comune, da cui un flusso di differenti varianti di prodotto può essere efficientemente ottenuto e sviluppato. Un numero sempre più elevato di realtà produttive sta introducendo le piattaforme di prodotto nel proprio contesto operativo. Tra queste si annoverano Sony, per la fabbricazione del Walkman, Kodak, Black & Decker e Hewlett-Packard. Dal punto di vista dei sistemi produttivi, i sistemi tradizionali mostrano numerosi limiti di adattamento alle nascenti esigenze di mercato. Questi sistemi possono essere efficacemente impiegati per effettuare produzione di massa delle piattaforme di prodotto, ma è necessario fare affidamento a sistemi di produzione avanzati per produrre i componenti rimanenti necessari a riconfigurare la piattaforma trasformandola in una variante finale.

Negli ultimi anni si stanno sviluppando sistemi produttivi di nuova generazione, tra cui i cosiddetti sistemi produttivi riconfigurabili (RMSs) e i sistemi di assemblaggio riconfigurabili (RASs) in grado di far fronte all'attuale dinamismo del mercato. Questa prerogativa viene raggiunta progettando il sistema produttivo e le macchine in esso incluse in modo che abbiano una struttura regolabile e modulare per far fronte efficacemente alla domanda di mercato dinamica e alla rapida introduzione di nuovi prodotti.

Obiettivo di questa tesi è proporre metodi e modelli innovativi a supporto dell'introduzione dei moderni principi di riconfigurabilità nella progettazione di prodotti e di sistemi produttivi avanzati, sia di fabbricazione che di assemblaggio, con l'obiettivo ultimo di migliorare le performance globali degli impianti industriali. Il raggiungimento di questi obiettivi è guidato non solo dall'interesse diretto delle moderne realtà industriali, ma anche dalla presenza di un forte numero di progetti di

finanziamento in diverse parti del mondo. Nel contesto dei progetti europei, esempi rilevanti sono i progetti *'Rapid reconfiguration of flexible production systems through capability-based adaptation, auto-configuration and integrated tools for production planning'* promosso nel 2015 e *'Skill-based propagation of plug-and produce devices in reconfigurable manufacturing systems'* e *'Adaptive automation in assembly for blue collar workers satisfaction in evolvable context'* promossi nel 2016.

L'attività di ricerca viene sviluppata seguendo uno schema logico-concettuale che evidenzia tre principali aree di ricerca: progettazione di piattaforme di prodotto modulari, progettazione di sistemi di produzione riconfigurabili e progettazione di sistemi di assemblaggio riconfigurabili. Ad ognuna di queste tre macro-aree è dedicato un capitolo di questa tesi, in cui, dopo aver analizzato lo stato dell'arte e i principali orientamenti della ricerca, vengono illustrate le attività di ricerca specifiche così come i principali risultati ottenuti e gli elementi di innovatività. I risultati ottenuti apportano contributi significativi in ambito scientifico e metodologico e supportano le aziende a livello strategico, tattico e operativo sia nella gestione della strategia produttiva che nella progettazione del sistema produttivo stesso.

Reconfigurability Principles in the Design and Management of Advanced Production Systems

By

Francesco Gabriele Galizia

Submitted in fulfilment of the requirements for the Degree of

Doctor of Philosophy

University of Padua

Doctoral School of Mechatronics and Product Innovation Engineering

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1 INTRODUCTION

To survive in modern competitive economy, satisfying customers request asking for a high number of customized variants in variable batches, industrial companies move from mass production to mass customization, which is defined as producing personalized products at a price similar to that of mass production (Daaboul et al., 2011). These trends inevitably affect both the production strategy to adopt and the production system design, i.e. manufacturing and assembly. From the production strategy viewpoint, companies traditionally adopt make to stock (MTS) and make to order (MTO) strategies. In particular, MTS minimizes lead-time but it becomes costly when the number of variants is large and it is also risky in presence of dynamic markets and short product life cycles. Conversely, by applying MTO the production does not start until a customer order is received. In this way, inventory can be significantly reduced but customer lead times increase (Rajagopalan, 2002, Olhager and Prajogo, 2012, Rafiei and Rabbani, 2012). Since modern manufacturing companies aim to optimizing warehouses management reducing stock, i.e. MTO goal, and to decreasing lead times, i.e. MTS goal, an effective trade-off production strategy best-managing such two conflicting objectives is expected. In this context, Delayed Product Differentiation (DPD) rises as an hybrid strategy that strives to reconcile the dual needs of high-variety and quick response time postponing the final product assembly differentiation point as much as possible (He et al., 1998) by using the concept of product platform (Gupta and Benjaafar, 2004). According to the original definition, a product platform is a set of sub-systems and interfaces that form a common structure from which a stream of derivative product variants can be efficiently produced and developed (Meyer and Lehnerd, 1997, Simpson et al., 2006). In particular, a common product platform is manufactured to stock (MTS) at the first stage of production which is then reconfigured into different products after demand is known at the second stage, i.e. MTO (Gupta and Benjaafar, 2004). A large number of industrial companies introduced product platforms as tool to reach the benefits of DPD, e.g. Sony, for the development of the Walkman (Sanderson and Uzumeri, 1995), Kodak, Black & Decker (Simpson et al., 2006) and Hewlett-Packard (Meyer, 1997) are relevant applications. From the production system viewpoint, while traditional manufacturing systems can be effectively used to mass produce product platforms, advanced manufacturing solutions are needed to produce the remaining components necessary to finalize the assembly of product variants (Huang et al., 2019). Among Next Generation Manufacturing Systems (NGMSs), in 1999 Professor Y. Koren from

University of Michigan introduced the Reconfigurable Manufacturing Systems (RMSs). According to the original definition, RMSs are designed '*at the outset for rapid change in structure, as well as in hardware and software components to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements*' (Koren et al., 1999, Koren, 2006). Such dynamic systems, with their six main features, i.e. modularity, integrability, diagnosibility, convertibility, customization and scalability, seem to have the right capacity and functionality to follow the market changes and, compared to traditional systems, allow producing a higher variety of customized products. Such systems cover also the assembly context in which are known as Reconfigurable Assembly Systems (RASs).

Even if the literature focusing on product platforms design is wide, most of the proposed methods are applied to industrial contexts characterized by limited number of product variants. Such issue does not reflect the operative situation because, nowadays, industrial companies have to manage hundreds variants. Moreover, effective methodologies supporting the design and management of reconfigurable manufacturing and assembly systems are missing and expected. According to the introduced research background, the aim of this Ph.D. dissertation is to proposing innovative methods, models and tools aided at including the emerging principles of reconfigurability in designing products and advanced production systems, i.e. manufacturing and assembly, to improve the overall performances along the industrial plants. Based on these statements, the research is motivated by a set of research questions that are discussed in detail in the next sub-chapter, followed by the research framework and the thesis outline.

1.1 RESEARCH QUESTIONS

This thesis is primarily motivated by the following overarching question.

How to effectively apply the emerging principles of reconfigurability to improve the overall performance of modern industrial companies which are facing radical industrial and market changes?

Such question is wide and can be approached by a variety of angles and standpoints. To narrow down the set of potential approaches to the problem, this question has been divided into two sub-questions.

RQ. 1: Concerning reconfigurability principles applied to products, how to design product platforms in modern high-variety industry?

Following this research question, the first purpose of this dissertation is to contribute to the further development of effective solutions for the design of product platforms in modern industry, which often needs to manage hundreds of different product variants.

RQ. 2: How to support industrial companies in the transition toward the adoption of reconfigurable manufacturing systems?

RQ. 3: How to support industrial companies in the transition toward the adoption of reconfigurable assembly systems?

Following these research questions, the second goal of this dissertation is to provide theoretical and practical solutions supporting industrial companies in the shift toward the adoption of advanced manufacturing and assembly paradigms.
As they are posed, the three research questions can encompass a wide range of related sub issues. For this reason, next Section 1.2 presents a research framework, in which a number of research levers are identified for each research question.

1.2 RESEARCH FRAMEWORK & THESIS OUTLINE

The research presented in this dissertation has been developed following the research framework of Figure 1. The matrix is organised into three main research levers: (1) design of modular product platforms, (2) design of reconfigurable manufacturing systems and (3) design of reconfigurable assembly systems.

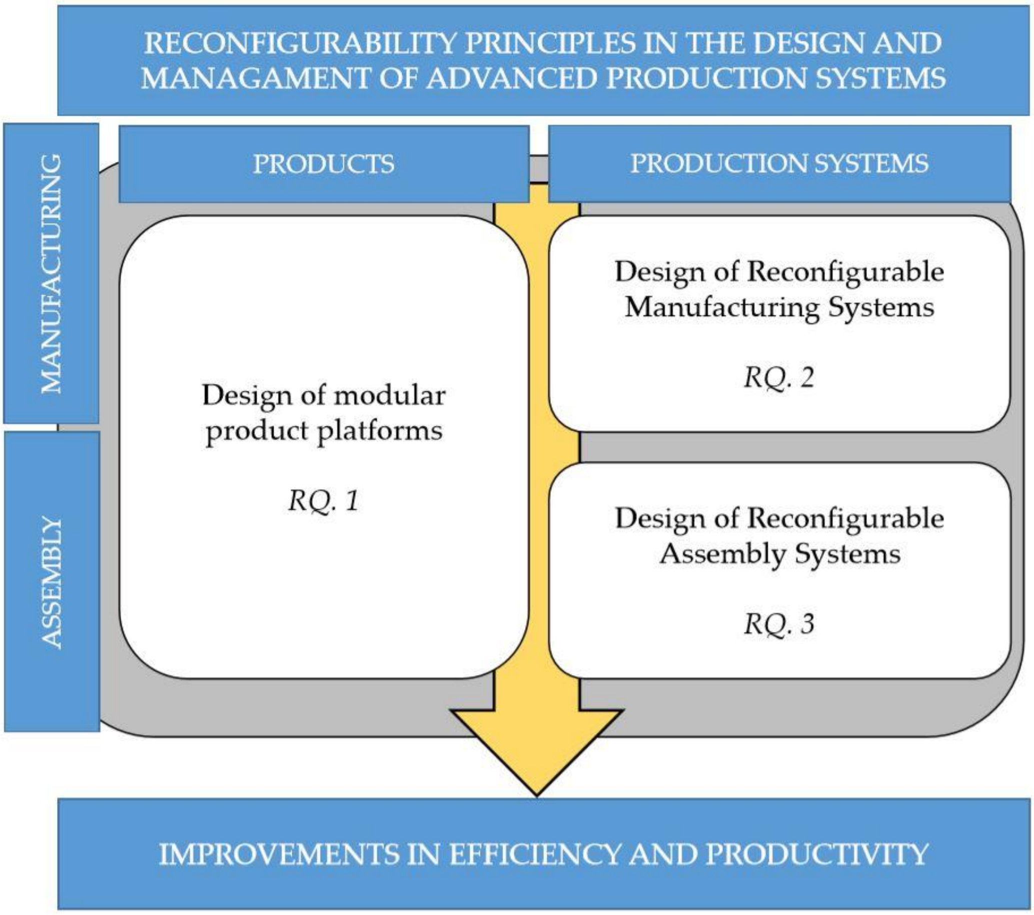

Figure 1: Research framework

To address *RQ. 1* one research lever is proposed, which explores methods and tools for the design of modular product platforms. To address *RQ. 2* and *RQ. 3* two research levers are proposed. The first focuses on the design and management of RMSs while the second on the design and management of RASs. Such research levers have been arranged in a sequence of chapters, as shown in Figure 2.

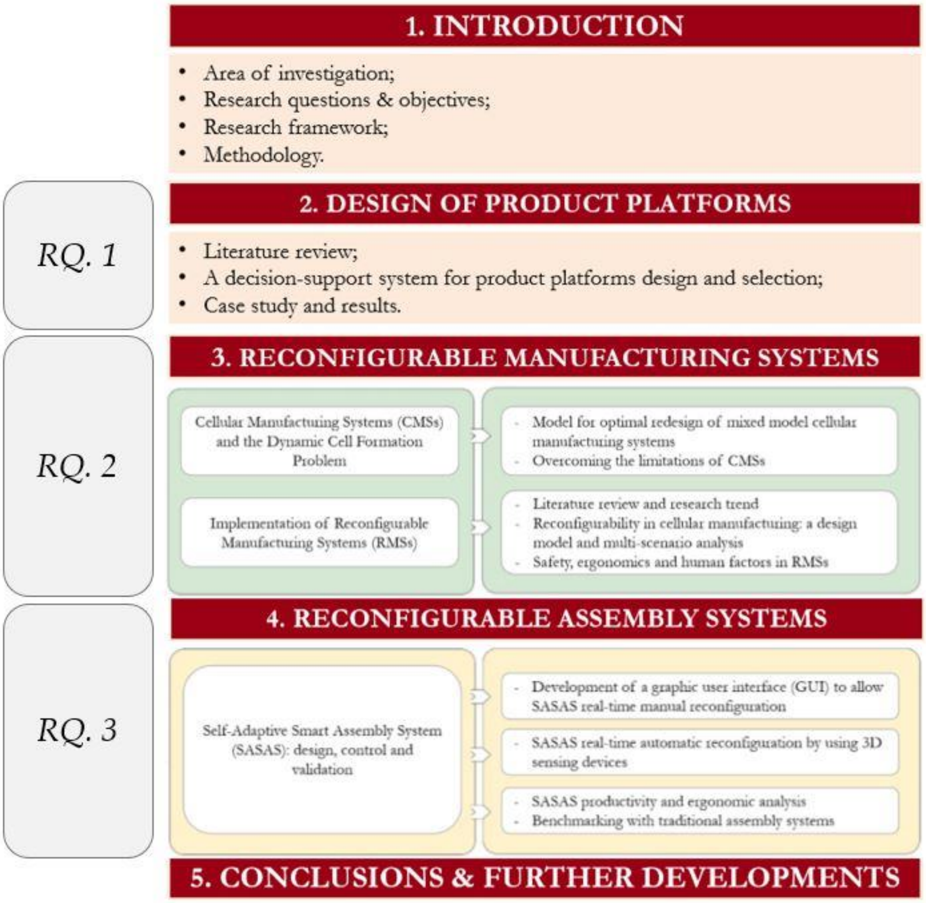

Figure 2: Thesis outline

Chapter 1 introduces this dissertation by outlining the area of investigation, the research questions the research framework and the thesis outline.

Chapter 2 addresses the *RQ. 1* and explores the design of modular product platforms proposing an integrated decision support system (DSS) for product platforms design and selection in high variety manufacturing to best manage the trade-off between platforms variety and number of assembly/disassembly tasks needed to customize the platforms into the final product variants. In addition, the developed DSS proposes new metrics to evaluate the effort to reconfigure the platforms into the final variants by considering the required number of assembly and disassembly tasks, i.e. Platforms Reconfiguration Index (PRI), and the ease of assembly and disassembly factors, i.e. Platforms Customisation Index (PCI). Such indices provide conditions that support industrial companies in determining, for each product variant, whether it is better to adopt DPD or assemble to order (ATO) strategy, and guide them in the selection of effective product platforms.

Chapter 3 addresses *RQ. 2* and deals with the design and management of a specific sub-category of reconfigurable systems, which are called Cellular Reconfigurable Manufacturing Systems (CRMSs). Such systems rise in the last few years as effective solutions able to overcoming the weaknesses of conventional Cellular Manufacturing Systems (CMSs) matching, at the same time, the dynamism of modern market. In particular, in conventional CMSs, once machine cells are designed, the physical relocation of the facilities included in each cell in response to new production requirements becomes difficult. To overcome such and other weaknesses, the literature firstly introduces the so-called Dynamic Cell Formation Problem (DCFP) aims at coping with variation in part mix and demand implementing machine relocations and duplications among the available manufacturing cells. However, to overcome the increase of the investment costs generated by the DCFP, RMSs and, in particular, CRMSs rise in the last few decades as innovative manufacturing systems in which machine modification is performed instead of their relocation and/or duplication with the aim to enhance machine capabilities to process a wider range of production tasks. Starting from this background, Chapter 3 firstly explores the DCFP proposing a mathematical model supporting the redesign of cellular manufacturing systems through machine relocations/duplications. Afterwards, following the recent shift toward the reconfigurable manufacturing paradigm, the concept of reconfigurability is revised and a design model supporting the optimal design and management of CRMSs is introduced. In the design and management of these systems, a relevant aspect to consider is the human contribution. In fact, despite their automation level, CRMSs still require actions by human operators, e.g. material handling, WIP load/unload, tool setup, etc, rising safety and ergonomics issues because of the human-machine interaction and cooperation. To managing this aspect, the last part of this chapter proposes an innovative methodological framework supporting the integration of safety, ergonomics and human factors in CRMSs.

Chapter 4 addresses the *RQ. 3* focusing on the introduction of reconfigurability principles in the assembly domain aiming at designing advanced assembly systems which are rapidly real-time reconfigurable according to product features, e.g. size, work cycle, and human operator features, e.g. anthropometric measurements. To this aim, a conceptual framework is defined to support industrial companies to achieving real-time manual and automatic reconfiguration of such systems. The proposed framework is, then, applied to a real prototypal reconfigurable assembly cell, called Self-Adaptive Smart Assembly System. An easy-to-use GUI and a tool based on the use of 3D sensing devices, i.e. Microsoft Kinect™, are developed to allow an efficient assembly system reconfiguration and are validated by simulating the assembly of two different products, i.e. an industrial chiller and a centrifugal electric pump.

Chapter 5 concludes the dissertation highlighting the obtained results, the managerial insights and proposing potential future developments.

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2 Design and Management of Modular Product Platforms

This chapter addresses the *RQ. 1* focusing on the development of effective methodologies for product platforms design and selection in high-variety manufacturing as a relevant solution to manage the modern dynamic markets, to decrease lead-time and to delay product differentiation. An integrated decision support system (DSS) is developed supporting the platforms design procedure in modern industry best managing the trade-off between variety and the number of assembly/disassembly tasks to perform to customize the platforms into the final variants. The content is based on the research paper (Galizia, F. G., ElMaraghy, H., Bortolini, M., Mora, C. (2019). Product platforms design, selection and customization in high-variety manufacturing, *International Journal of Production Research*, in press).

In modern industry, manufacturers face with a high level of product innovation, market globalization, dynamic customer demand and technological advancements (Shou et al., 2017, Bortolini et al., 2018). These trends encourage industrial companies to adopt the mass customization paradigm to meet every customers' request and satisfy their individual needs (Gilmore, 1997). The main advantage of such strategy is to provide different goods to customers with the same quality and prices of the mass-produced products (Su et al., 2010). In this scenario, companies are switching from Make-To-Stock (MTS) and Make-To-Order (MTO) strategies to Delay Product Differentiation (DPD) in order to implement mass customization. DPD is a hybrid strategy that strives to reconcile the dual needs of high-variety and quick response time, by utilizing the concept of product platforms (Gupta and Benjaafar, 2004). A product platform is defined as a set of sub-systems and interfaces that form a common structure from which a stream of derivative product variants can be efficiently produced and developed (Meyer and Lehnerd, 1997, Simpson et al., 2006). In particular, a common product platform is manufactured to stock (MTS) in the first stage of production which is then differentiated into different products after demand is known in the second stage, i.e. manufactured to order (MTO) (Gupta and Benjaafar, 2004). A large number of industrial companies introduced product platforms as tool to reach the benefits of DPD. Sony, for the development of the Walkman (Sanderson and Uzumeri, 1995), Kodak, Black & Decker (Simpson et al., 2006) and Hewlett-Packard

(Meyer, 1997) are among the most relevant applications. In this chapter, an integrated decision support system (DSS) for product platforms design and selection in high-variety manufacturing is proposed to best manage the trade-off between platforms variety and number of assembly/disassembly tasks needed to customize the platforms into the final product variants. The Median-Joining Phylogenetic Networks (MJPN) supports the design phase by identifying the different product platforms, their number and composition, and the use of both assembly and disassembly to customize them into product variants. MJPN methodology is traditionally used in biology to predict the living species' ancestry by linking them to their descendants, through gaining and losing of genes (Bandelt et al., 1999, Hanafy and ElMaraghy, 2015), but its use in the assembly and manufacturing field is relatively new. To the Authors' knowledge, the unique contribution of its use in this field is found in Hanafy and ElMaraghy (2015). The methodology builds the so-called phylogenetic network tree, which shows the transformation of each platform into a variant through gaining and losing of components and, unlike most models found in literature, it does not require in advance the specification of the number of platforms to develop. The developed DSS proposes two new metrics to evaluate the effort to reconfigure the platform into a variant by considering the required number of assembly and disassembly tasks, i.e. Platforms Reconfiguration Index (PRI), and the ease of assembly and disassembly factors, i.e. Platforms Customization Index (PCI), at each level of the phylogenetic tree. Such indices provide conditions that support industrial companies in determining, for each product variant, whether it is better to adopt DPD or assemble to order (ATO) strategy, and guide them in the selection of effective product platforms. To illustrate and validate the steps of the proposed DSS, it is applied to a large real case study involving manufacturing 1553 items, representative of a Small & Medium Enterprise (SME).

The remainder of this chapter is organised as follows: Section 2.1 reviews the relevant literature. Section 2.2 presents the original DSS for product platforms design and selection, while Section 2.3 presents the DSS application to a real industrial case study. Finally, Section 2.4 concludes the chapter highlighting key outcomes and conclusions.

2.1 LITERATURE REVIEW

This section is organized into two parts. The former explores the DPD concept and the methods and techniques used for product platforms design, and the latter introduces metrics and indices developed to model the assembly and disassembly tasks, which represent the two operations to perform in order to customize a platform into a variant.

2.1.1 Delayed Product Differentiation and product platform concept

The ability of a manufacturing system to have high product variety and short lead times offers a competitive advantage. Industrial companies that strive to reach this ability prefer to produce a limited portfolio of products (Gupta and Benjaafar, 2004). In this context, items can be produced to stock (MTS) to minimize lead times, but such a solution becomes costly when the number of final products is large and it is also risky in presence of dynamic market demand and short product life cycles. Manufacture to order (MTO) is another key production strategy where production does not start until a customer order is received. Applying this strategy, inventory can be reduced but customer lead times increase (Rajagopalan, 2002, Rafiei and Rabbani, 2012, Olhager and Prajogo, 2012). Delayed Product Differentiation (DPD) is a hybrid strategy that postpones the final product assembly differentiation point as much as possible (He et al., 1998). Postponement can be divided into form postponement and time postponement (Zinn and Bowersox, 1988, Yang et al., 2004). Blecker and Abdelkafi (2006) state that form postponement describes all the activities initiated after the arrival of customer orders. Hsu and Wang (2004) propose a dynamic programming model for the tactical planning using an AND/OR graph to determine the product differentiation points. The impact of deferment on capital investment and inventory risk-pooling effects are quantified and incorporated in the model. Swaminathan and Tayur (1998) introduce a model to find the best configuration and inventory level of product platforms and compare the performance of such production strategy with that of MTO and Assemble-To-Order (ATO) processes providing managerial insights into the conditions under which one may be better than the other. He and Babayan (2002) state that the successful implementation of DPD strategy lies in efficient scheduling of the manufacturing system. In their study, they define and solve the scheduling problems in implementing a DPD strategy in a general flexible manufacturing systems consisting of machining and assembly stations. Ko and Jack Hu (2008) propose a binary integer programming model for task-machine assignment and workload balancing in complex asymmetric configurations, since such configurations have often been used for delayed product differentiation. AlGeddawy and ElMaraghy (2010a) introduce an innovative design methodology to derive and represent an assembly line layout for delayed products differentiation by using cladistics classification. The resulting cladogram identifies the points of DPD and resembles the physical assembly system layout and was demonstrated for a family of electric kettle variants. AlGeddawy and ElMaraghy (2010b) extend this cladistics model by adding product assembly line balancing constraints to the classification algorithm. Hanafy and ElMaraghy (2015) develop a methodology for assembly line layout for DPD using phylogenetic networks. The proposed model is used to design product platforms and determine the assembly line layout of modular product families.

The Delayed Product Differentiation strategy aims to reconcile the dual needs of high-variety and quick response time by introducing the concept of product platforms (Gupta and Benjaafar, 2004). Product platform is defined as a set of sub-systems and interfaces that form a common structure from which a stream of derivative products can be efficiently produced and developed (Meyer and Lehnerd, 1997). Khajavirad et al. (2009) define a multi-objective genetic algorithm to design product families and product platforms of universal electric motors. The objective function maximizes product efficiency and commonality among modules along with decreasing motors' weight. Jose and Tollenaere (2005) propose an in-depth literature review of the product platform concept focusing on the efficient product family development. They found that it is necessary to best balance the introduction of new techniques to increase components commonality and increasing products distinctiveness. Williams et al. (2007) introduce the Product Platform Constructal Theory Method (PPCTM) as a technique enabling the designers to develop platforms for customizable products and apply this method to determine a platform map of a cantilever beam. Yu et al. (2007) use the Design Structure Matrix (DSM) combined with GA to design common platforms for complex products. Moon et al. (2008) develop a multi-agent model to configure product platforms considering the functional model. However, the model cannot handle large product families. Ben-Arieh et al. (2009) propose a mathematical model to configure single and multiple platforms by adding and/or removing components to/from the platforms to get the final variants. However, the model requires the specification of the expected number of platforms a priori. Furthermore, the proposed model is not scalable and requires a formulation based on the application of a genetic algorithm (GA) to solve problems having a large number of products and components. While the most common product platform concept is based on adding or assembling components to the platform to produce product variants, the recent literature proposes the idea of both assembling and disassembling components to/from platforms to customize them and get the final variants (Ben-Arieh et al., 2009, Mesa et al., 2014, Hanafi and ElMaraghy, 2015, Mesa et al., 2015, Mesa et al., 2017). This emerging strategy based on both assembly and disassembly operations leads to an increase in the number of components in a platform, which means more delay in product differentiation and, consequently, the mass production of a larger product portion, i.e. the platform. The assembly/disassembly of components to/from a platform to obtain product variants is very similar to the concept of evolution, i.e. acquiring and losing characteristics in biological organisms. Phylogenetic networks are used to trace this kind of evolution and predict the living species' ancestry by linking them to their descendants, through gaining and losing of genes. Although the research in DPD is rich, some research gaps remain. In particular, the use of both assembly and disassembly to arrive at the final product variant, which can increase the number of components shared across a product family, is rarely used. This strategy is called "Customized Platforms To Order (CPTO)" (Aljorephani, 2017).

2.1.2 Effort in assembly/disassembly tasks

An important topic in the study of product platforms design using both assembly and disassembly is the effort involved in reconfiguring and customizing the platforms to get the final variants. The effort associated with the reconfiguration can be modeled in different ways, considering for example the number of assembly/disassembly tasks to be performed to change it from a platform to a product variant, and/or assessing the difficulty to assemble and/or disassemble components to/from the platform. Focusing on the assembly tasks, Samy and ElMaraghy (2010) propose a product model to assess assembly complexity of individual parts taking into account the principles of Design for Assembly (DFA). They demonstrate how the model would lead to a reduction of product assembly complexity and the associated cost. Miller et al. (2012) explore the automation of the estimated assembly time by reducing the level of design details required. In particular, they define a complexity metric through artificial neural networks to measure such assembly time. A similar study is proposed by Owensby and Summers (2013). They present an automated tool for estimating assembly times of products based on a complexity metric model. Orfi et al. (2011) introduce five main dimensions of product complexity identifying different complexity sources in product design, development, manufacturing and assembly. Their overall goal is to define a unified product complexity metric to be used as a tool to improve product design and manage product complexity. Rodriguez-Toro et al. (2003) review the concept of complexity to support assembly-oriented design and to guide the designers in manufacturing a product with an effective balance of manufacturing and assembly difficulty. Thevenot and Simpson (2006) tackle the product family design problem and propose relevant commonality indices to assess the amount of commonality within a product family, e.g. the developed Percent Commonality Index from the assembly viewpoint measures the percentage of common assembly sequences among products. Concerning disassembly, Lee and Ishii (1997) and Kroll and Carver (1999) propose complexity metrics associated with the final disposal phase of the products. Boothroyd and Alting (1992) and Bryan et al. (2007) highlight the importance of integrating parts when possible to reduce the assembly and disassembly tasks during the early design stages. However, research assessing the effort associated with both assembly/disassembly tasks are rare. Mesa et al. (2017) propose a metric to assess the complexity of assembly/disassembly tasks in open architecture products.

Starting from this scenario, the proposed DSS provides two new metrics integrated with the product platform design that evaluate the effort to reconfigure the platforms into variants at each level of the phylogenetic tree, i.e. the Platforms Reconfiguration Index (PRI) and the Platform Customization Index (PCI). The former considers the assembly and disassembly tasks involved into platform reconfiguration while the latter considers the ease of assembly and disassembly factors, in addition to their number, since they affect the time it takes to accomplish these tasks. Next section describes the proposed DSS.

2.2 A Decision-Support System for Product Platform Design and Selection

In this chapter, a decision support system (DSS) is proposed to guide industrial companies and practitioners in the design and selection of efficient product platforms, managing the trade-off between platforms variety and required platforms customization effort represented by the time and difficulty of assembly and disassembly tasks. Product platforms are designed by applying the Median Joining Phylogenetic Networks (MJPN). This methodology is traditionally used in biology and its use in the manufacturing and assembly field is relatively new. In particular, it is used in the design phase to define the number and composition of different platforms using both assembly and disassembly to customize the platforms into product variants as needed. In the proposed DSS, it is assumed that components can be disassembled without damage (e.g. fastening), hence, preserving product quality integrity during platforms reconfiguration.

2.2.1 Methodology

The phylogenetic networks concept has continued to evolve over time, due to the huge number of derivatives obtained from the first concept of unity of species' origins by Darwin (Hanafy and ElMaraghy, 2015). Such networks can be classified in two categories: rooted and unrooted networks (Huson and Scornavacca, 2011). The cladistics classification methodology is the main branch of rooted phylogenetic networks and major literature contributions on the use of such approach in manufacturing and assembly field are found in AlGeddawy and ElMaraghy (2010a) and AlGeddawy and ElMaraghy (2010b). The MJPN algorithm belongs to the unrooted phylogenetic networks. It has been used in biology to trace and classify DNA sequences according to their relationship to hypothetical ancestral nodes, called median vectors (MV) (Bandelt et al., 1999). Such algorithm builds a network tree (Figure 3) that relates DNA sequences, which in this case are the product variants (from P1 to P10), to each other by the definition of MVs, which represent the product platforms (from PL1 to PL3) through the majority consensus concept. Specifically, majority consensus median is the median point that links the products by a product representing all common parts between products, i.e. the normal family platform, as well as the components that the majority of products possesses. Next Figure 3 discusses the relevance of MJPN to platform formation by showing some products (similar to biological descendants), each of which is composed by a binary combination of assembling (adding) or disassembling (removing) a component (gene) from the defining binary string. The platform, i.e. the ancestor, is considered the nearest to every product. After the assembly of platform/platforms, it/they can easily be used in the assembly of product/products, by adding or removing components. Several factors must be considered when using this method for forming product variants:

- modularity of components;
- assembly/disassembly time ratio;
- presence of demand uncertainty for certain product variants.

Network 5.0 software (Fluxus-engineering.com 2012) is used to build the phylogenetic network. This software is able to compute two main types of algorithms: the median-joining to build a full joined network of species and its inferred ancestry, and the reduced-median to perform the same analysis but only in case of difficulties in interpreting the full median-joining network.

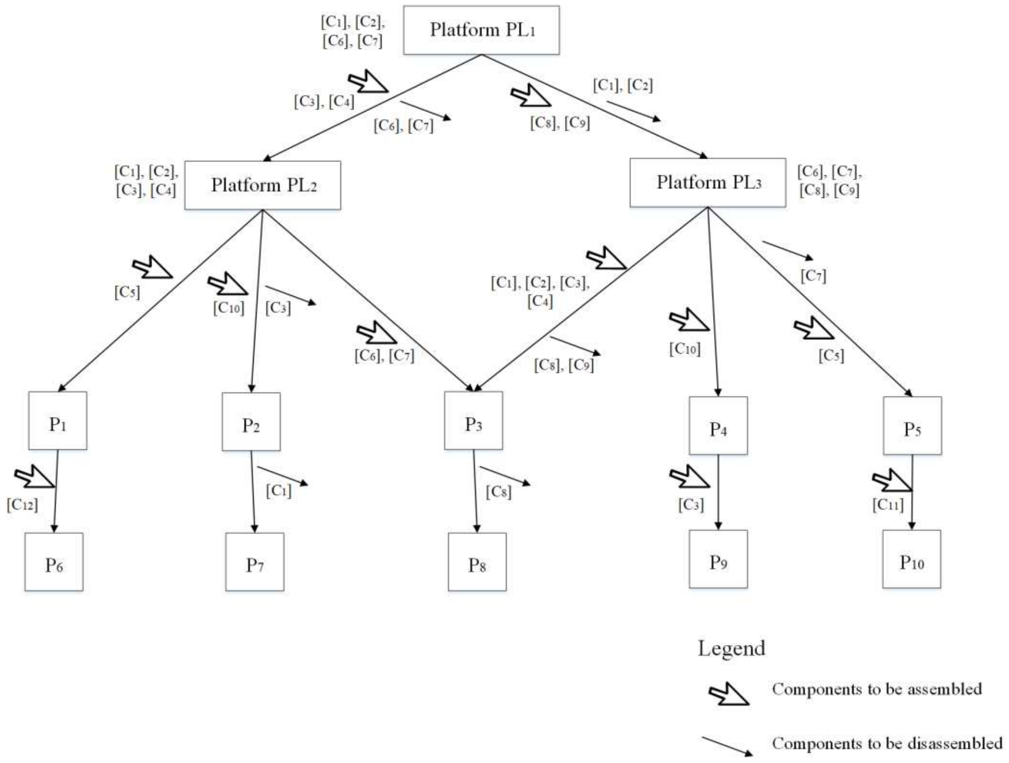

Figure 3: Example of phylogenetic network tree for a product family and its variants and components

In the example shown in Figure 3, the product family is composed of ten product variants (indicated from P1 to P10) and of a total number of twelve components (indicated from C1 to C12). The MJPN algorithm creates three product platforms (indicated from PL1 to PL3) for this family.

2.2.2 The proposed DSS

Figure 4 shows a general schematic of the proposed methodology, which has four main steps:

- Step I: Product family definition
- Step II: Product platforms design and definition of assembly/disassembly relationships
- Step III: Platforms variety and Platforms customization effort analysis
- Step IV: Selection of best product platforms

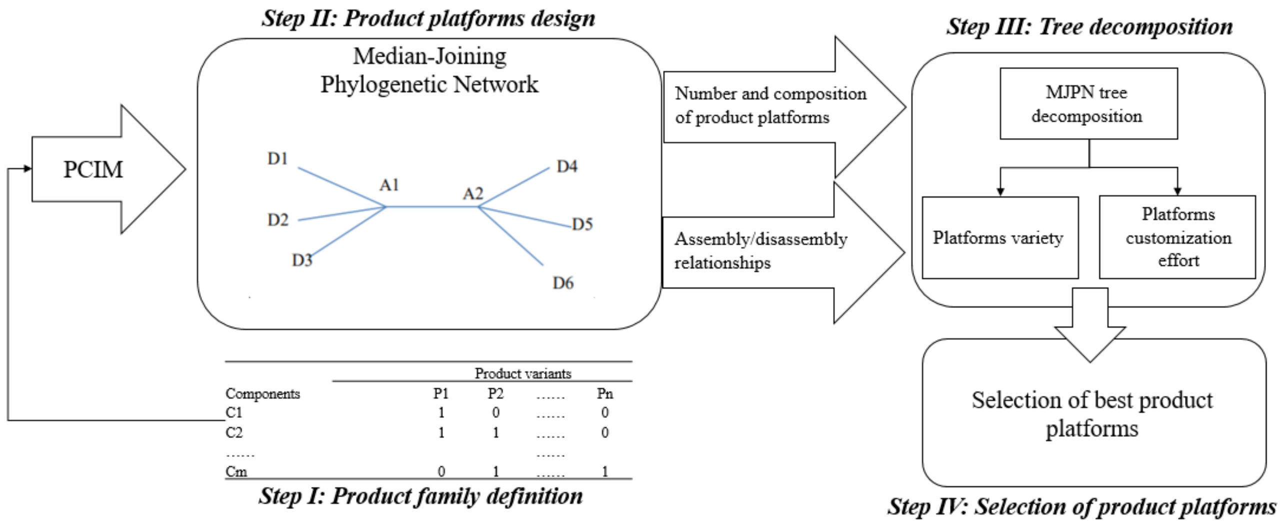

Figure 4: Schematic of the proposed decision-support system (DSS)

2.2.2.1 *Product family definition*

The methodology starts with the selection of a product family for which the introduction of product platforms is required. The input of this step is the generic bill of materials (BOM) for each product belonging to the family while the output is the definition of the PCIM. Considering n product variants from 1 to P_n and m components in the product variant from 1 to C_m, the PCIM includes X_{mn} binary elements such that:

$$X_{mn} = \begin{cases} 1, & \text{if Cm is in Pn} \\ 0, & \text{otherwise} \end{cases}$$

2.2.2.2 *Product platforms design and definition of assembly/disassembly relationships*

In this step, the Median-Joining Phylogenetic Networks (MJPN) algorithm is applied to design the product platforms for the considered product family. As shown in Figure 4, the algorithm input is the PCIM. It builds the phylogenetic network tree, containing the number and the composition of the generated product platforms as well as the assembly/disassembly relationships. Such relationships are crucial to visualize the specific platforms involved in each product reconfiguration and specify which component to add or remove to customize the platform to a product variant or to change from a product variant to a new variant configuration (Mesa et al., 2017).

2.2.2.3 *Platforms variety and platforms customization effort analysis*

The third step of the proposed decision support system (DSS) manages the phylogenetic tree decomposition supporting the product platforms selection process. Product platforms have to be designed and selected to maximize the number of components in each platform in order to reduce the number of assembly/disassembly tasks to be performed to obtain the desired product variant while minimizing the number of different platforms to be assembled and stored in order to reduce variety, inventory costs and storage space. Step III addresses this trade-off: the phylogenetic tree obtained in the second step (Figure 3) is decomposed into multiple levels (Figure 5) from the native platforms (Level 1) to the final variants (Level L). A native platform is a platform that has no incoming arrows (PL_1 in the reference example), while a platform or a product variant belongs to level L if it does not have outgoing arrows (from P_6 to P_{10} in the referenced example).

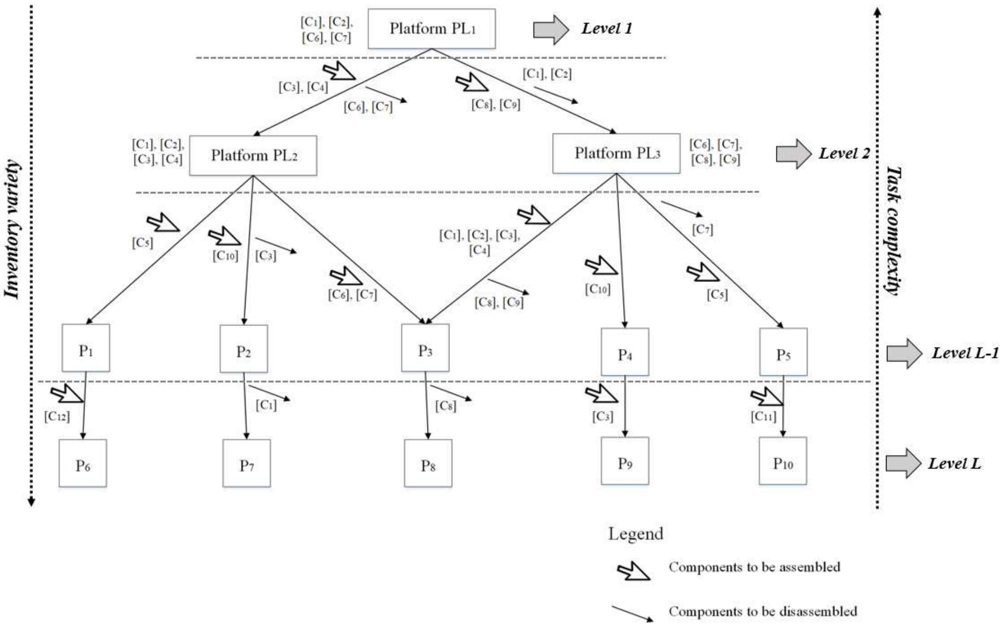

Figure 5: MJPN tree decomposition for platforms selection

Each level corresponds to a different trade-off between the number of types of platforms to be stored, i.e. *platforms variety*, and the number of assembly/disassembly tasks to convert platforms to variants, i.e. *platforms customization effort*. In particular, as platforms number/variety increases from Level 1 to Level L, the platforms customization effort decreases. The platforms selection procedure is characterized by the following steps:

1. MJPN tree decomposition into levels (l = 1 ... L);
2. For all levels (from 1 to L-1), determine platforms variety and platforms customization effort. Platforms variety represents the number of types of platforms formed in the considered level. The platforms customization effort is assessed by determining the proposed Platforms Reconfiguration Index (PRI) and Platforms Customization Index (PCI). These indices model the effort needed to reconfigure each platform into a variant thus they are indicative of the cost of platform reconfiguration.

Platforms Reconfiguration Index (PRI)

The Platforms Reconfiguration Index (PRI) is an index capable of capturing the effort to reconfigure the product platform into a specific variant by considering the number required of assembly and disassembly tasks. The mathematical formulation of PRI follows:

Indices

v	variants $v = 1, \dots, V$
p	product platform $p = 1, \dots, P$

Parameters

NCA_{pv}	number of components to assemble to platform p to get variant v
NCD_{pv}	number of components to disassemble from platform p to get variant v
NCV_v	number of components per variant v
PRI_{vp}	Platform Reconfiguration Index (to get variant v from platform p)
PRI	Global Platforms Reconfiguration Index for all platforms

The mathematical formulation of the PRI index to customize a specific platform into a variant is expressed by Equation 1:

$$PRI_{vp} = \frac{NCA_{pv} + NCD_{pv}}{NCV_v} \qquad \forall\, v = 1, \dots, V \qquad (1)$$

The condition $NCA_{pv} + NCD_{pv} < NCV_v$ determines, for each specific product variant, whether it is better to adopt delayed product differentiation (DPD) or assemble to order (ATO) strategy.

Specifically, if the condition is true, DPD strategy would be suitable for implementation in the case company, otherwise ATO would be preferable. Therefore, to determine the threshold values of PRI_{vp}, the following three cases are considered:

- <u>Total overlap</u> between product platform and product variant: in this case $NCA_{pv} = NCD_{pv} = 0$ and $PRI_{vp} = 0$ and no effort is required for platform reconfiguration;
- <u>No overlap</u> between product platform and product variant: in this case the condition $NCA_{pv} + NCD_{pv} > NCV_v$ is true. This implies that the ATO strategy is to be implemented. Considering NCA_{pv} and NCD_{pv} as the number of components involved in the assembly/disassembly tasks, $NCD_{pv} = 0$ and $NCA_{pv} = NCV_v$. Hence, $PRI_{vp} = 1$. In this case, the required platform reconfiguration effort is maximum;
- <u>Partial overlap</u> between product platform and product variant: the variant and the product platform share some components, and may require some assembly and/or disassembly tasks to be performed, in which case $PRI_{vp} = \frac{NCA_{pv}+NCD_{pv}}{NCV_v}$.

To summarize $0 \leq PRI_{vp} \leq 1$. PRI_{vp} indices can be further computed over the variants to get an average PRI index for each level of the phylogenetic tree, as expressed in Equation 2:

$$PRI = \frac{\sum_{v=1}^{V} PRI_{vp}}{V} \qquad (2)$$

Platforms Customization Index (PCI)

A Platforms Customization Index (PCI) is proposed by considering the ease of assembly and disassembly factors, in addition to their number, since they affect the time it takes to accomplish these tasks. The time needed to customize the product platform by performing additional assembly tasks can be represented by the value of their respective two-digits assembly codes introduced by Boothroyd et al., 2011. The value of these digits is representative of the ease/difficulty and of the time needed for manual/automatic handling and insertion of each component during assembly operations. For example, assume for a given part that the manual or robotic handling code is 31 and assembly by insertion code is 26, then the assembly effort for this one task would be (3+1) + (2+6) = 12. Each code digit has a value in the 0-9 range, therefore, 36 represents the maximum value (maximum difficulty) of manual/automatic handling and insertion for each component. The time needed for disassembly tasks is estimated by applying the Unfastening Effort Model (U-Effort model) and the corresponding Unfastening Effort Index (UFI) introduced by Sodhi et al. (2004). For each fastener type used for disassembly, the U-Effort model identifies several causal attributes and uses these to derive the UFI score for a given disassembly case. The UFI scale is defined in the 0-100 range, where 100 represents the most difficult disassembly case. It is appropriate to use the U-Effort model since the majority of non-destructive disassembly operations - a pre-requisite for use of the platform assembly/disassembly approach - involve unfastening. The mathematical formulation of PCI is as follows:

Indices

c	components $c = 1, \dots, C$
v	variants $v = 1, \dots, V$
p	product platform $p = 1, \dots, P$

Parameters

ACI_{cpv}	assembly customization index (handling and insertion two-digit codes for assembly of component c to platform p to get variant v)
DCI_{cpv}	disassembly customization index (U-effort index for disassembly of component c from platform p to get variant v)
PCI	Platforms Customization Index for all platforms

$$PCI = \frac{\sum_{v=1}^{V}\left[\left(\sum_{c=1}^{C} ACI_{cpv}\right) + \left(\sum_{c=1}^{C} DCI_{cpv}\right)\right]}{\max(ACI_{cpv}, DCI_{cpv})} \qquad (3)$$

PRI and PCI values are calculated for all levels $l = 1, \dots, L-1$ of the phylogenetic network tree. Level L is not considered in the analysis since the selection and subsequent storage of items, i.e. product variants, belonging to this level corresponds to the initial case of MTS strategy. The outputs of this step, for each level, are the values of platforms variety and platforms customization effort.

2.2.2.4 *Selection of best product platforms*

In this step, the decision maker is able to select a proper product platforms configuration, which best balances such a trade-off using the values of platforms reconfiguration and platforms customization effort indices for each level of the phylogenetic network tree. This decision is not universal but is specific to the industrial company and products under consideration. After the selection phase, the company manufactures and stocks the platforms following the MTS strategy. Platforms are modular entities composed of the components most shared within the product family and can be reconfigured into different variants by assembly and disassembly of components when a customer order is received. As stated in section 2.2, it is assumed that components can be disassembled from the platforms without damage through manual assembly operations while products including permanent joining operations, e.g. welding, would not be suitable. This condition prevents damages and ensures high integrity and quality during platforms reconfigurations.

2.3 Industrial Case Study

A real industrial case study is considered to illustrate and validate the steps of the proposed decision support system (DSS). The case company manufactures pipe fittings and valves in different plastic materials using injection molding machines and each product model is available in different sizes, colours and materials for a total of 1553 items, which represents very high product variety. Production volume and demand trend are shown in Figure 6 and Figure 7.

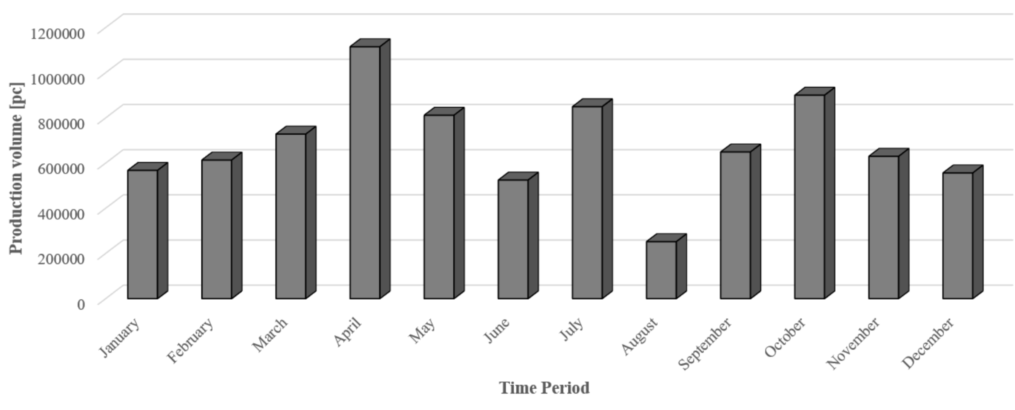

Figure 6: Annual production volume variation for the case company

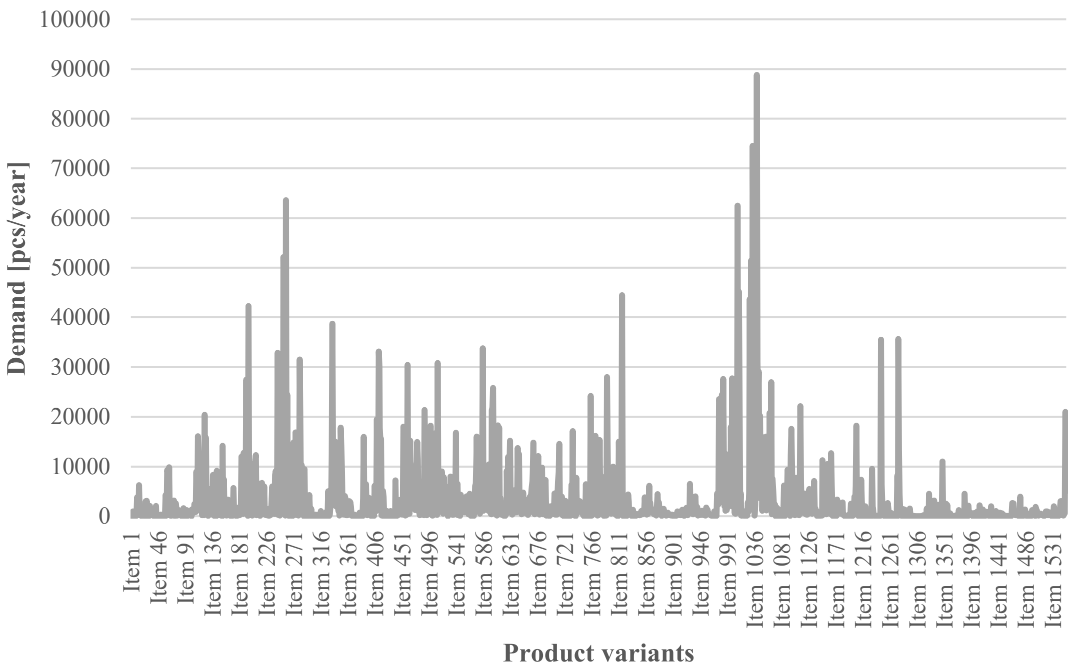

Figure 7: Annual product variants demand trend

The company stocks the products, after production of individual product variants, following the MTS strategy. The decision to implement such strategy has lead, as primary effect, to the occupation of a large storage space and high level of inventory. Since plastic valves produce a large proportion of company revenues and customers ask for medium volume batches of such products, the industrial company is looking to introduce product platforms for this family of valves to make it possible to delay products differentiation and manufacture and customize products platforms to order, hence, increasing operational efficiency and reducing production and storage costs.

2.3.1 Product family definition

Case studies found in literature use product families with limited number of product variants, each of which is typically made of few components. To address this deficiency, a very large products family is considered in this study. In particular, the family of valves consists of 16 models, each of which is available in different materials, sizes and colours. Figure 8 shows an example of one of these valves, including the BOM, the finished product and the components description. Thirty-eight (38) product variants exist, each of which is composed of a combination from 9 to 14 components, for a total of 93 components most of which are symmetric around the axis of insertion. The PCIM is the input to the MJPN algorithm for constructing the phylogenetic network. In the following sections, valve variants are indicated from P1 to P38 and the sub-components from C1 to C93.

Component number	*Component name*
1	Handle
2	Pin O-ring gasket
3	Pin
4	Body
5	PTFE gasket
6	Ball
7	Gasket supporting 5
8	Radial sealing O-ring gasket
9	Bush

Figure 8: Example of a valve variant and its components

2.3.2 Valves platform design and definition of assembly/disassembly relationships

The MJPN algorithm creates 18 consensus medians/platforms, indicated from Platform 1 to Platform 18. The assembly and disassembly relationships resulting from platforms reconfiguration are reported in the phylogenetic network tree (Figure 9) while the platforms composition is reported in Table 1.

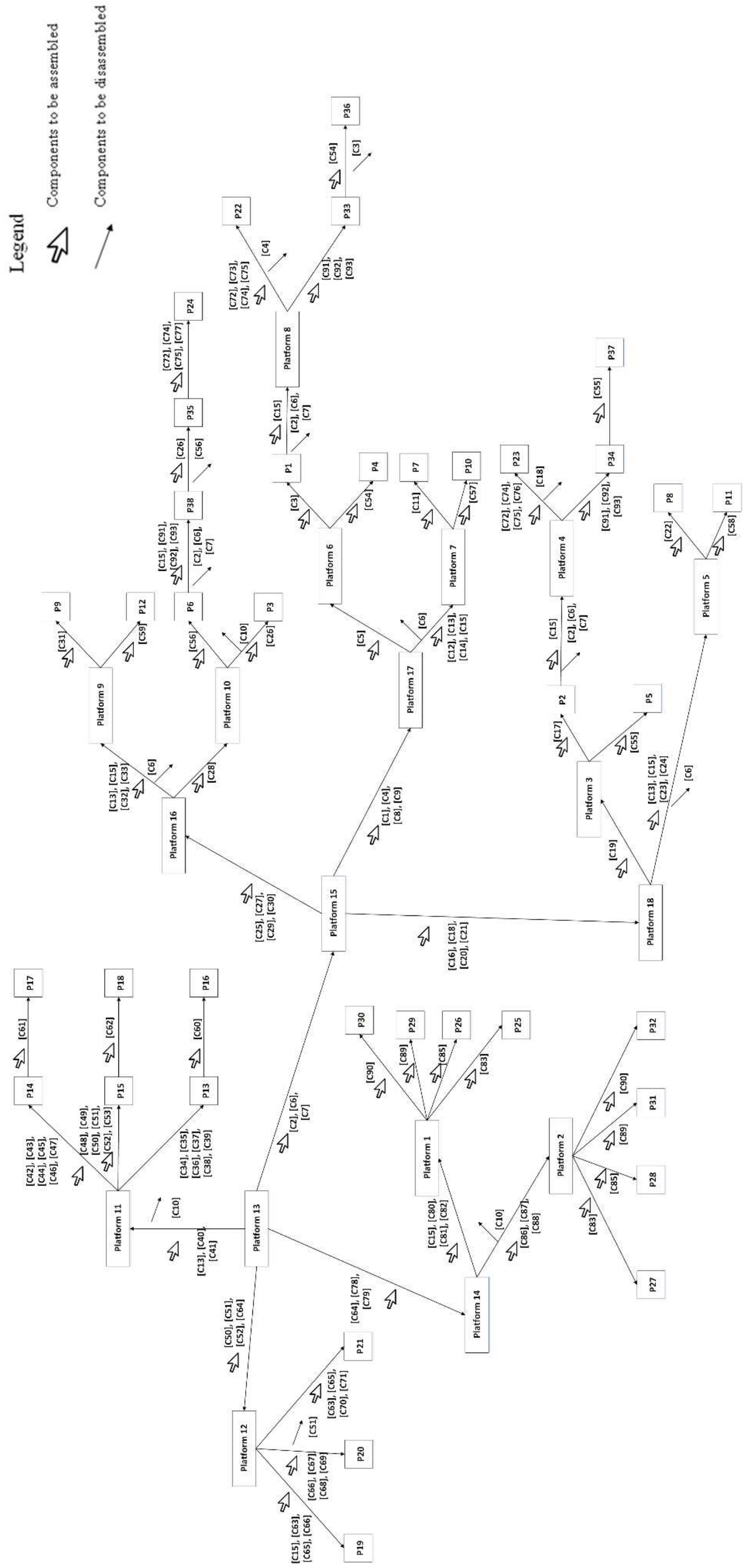

Figure 9: Phylogenetic network tree result for the family of plastic valves

Table 1: Plastic valves platforms composition

Platform	***Components***
Platform 1	C10, C15, C78, C79, C80, C81, C82, C84
Platform 2	C78, C79, C84, C86, C87, C88
Platform 3	C2, C6, C7, C10, C16, C18, C19, C20, C21
Platform 4	C10, C15, C16, C17, C18, C19, C20, C21
Platform 5	C2, C7, C10, C13, C15, C16, C18, C20, C21, C23, C24
Platform 6	C1, C2, C4, C5, C6, C7, C8, C9, C10
Platform 7	C1, C2, C4, C7, C8, C9, C10, C12, C13, C14, C15
Platform 8	C1, C3, C4, C5, C8, C9, C10, C15
Platform 9	C2, C7, C10, C13, C15, C25, C27, C29, C30, C32, C33
Platform 10	C2, C6, C7, C10, C25, C27, C28, C29, C30
Platform 11	C13, C40, C41
Platform 12	C10, C50, C51, C52, C64
Platform 13	C10
Platform 14	C10, C78, C79, C84
Platform 15	C2, C6, C7, C20
Platform 16	C2, C6, C7, C10, C25, C27, C29, C30
Platform 17	C1, C2, C4, C6, C7, C8, C9, C10
Platform 18	C2, C6, C7, C10, C16, C18, C20, C21

2.3.3 Platforms variety and platforms customization effort analysis

The phylogenetic tree obtained in Step II (Figure 9) is decomposed into multiple levels. In this case study, 7 levels result from tree decomposition ($l = 1 \ldots 7$) and for all levels $l = 1, \ldots, 6$ platforms variety, PRI and PCI indices are computed. To determine the assembly customization indices (ACI) of the PCI, all the components involved in the assembly process are analyzed. In the manual handling phase, all these components can be grasped and manipulated by one hand without the aid of grasping tools, which corresponds to a digit value equal to 0. The second digit is determined considering that the components are easy to grasp and manipulate and their size is greater than 15 mm, hence, the corresponding digit code is 0. Therefore, the two-digits code for manual handling of each component is 00. For the manual insertion phase, a first digit code equal to 0 is selected since all the components and associated tools, including hands, can easily reach the desired insertion location. The second selected digit is 6 since holding down is required during subsequent processes to maintain orientation and stability at the location and no resistance occurs during insertion. The two-digits code for manual insertion of each component is 06, yielding an overall assembly effort for each component equal to (0+0)+(0+6)=6.

To evaluate the disassembly effort for the disassembly customization index (DCI), an UFI index equal to 6.12 is used for each component. Such value is defined by actually measuring the unit component disassembly time. This time is similar for all components since they have similar size and dimensions envelop, therefore, an average component disassembly time equal to 6.5 seconds is used. The corresponding UFI value, i.e. 6.12, is calculated by applying the following Equation 4, experimentally determined by Sodhi et al. (2004):

$$\text{Unfastening time(s)} = 5 + 0.04 \cdot \text{UFI}^2 \qquad (4)$$

Table 2 shows a summary of the main results. Tables containing both the detailed and global values of the indices are included in Appendix A.

Table 2: Indices for the L-1 levels of the phylogenetic tree

Level	***Formed platforms***	***N of components per platform***	***Platforms variety***	***Average components per platform***	***PRI***	***PCI***
Level 1	Plat13	1	1	1	0.94	21.97
Level 2	Plat11	3	4	4	0.75	18.71
	Plat12	5				
	Plat14	4				
	Plat15	4				
Level 3	P13	9	9	7.78	0.43	9.82
	P14	9				
	P15	9				
	Plat12	5				
	Plat1	8				

	Plat2	6				
	Plat16	8				
	Plat17	8				
	Plat18	8				
Level 4	P13	9	12	8.83	0.32	7.12
	P14	9				
	P15	9				
	Plat12	5				
	Plat1	8				
	Plat2	6				
	Plat9	11				
	Plat10	9				
	Plat6	9				
	Plat7	11				
	Plat3	9				
	Plat5	11				
Level 5	P13	9	15	8.87	0.2	4.20
	P14	9				
	P15	9				
	Plat12	5				
	Plat1	8				
	Plat2	6				
	Plat9	11				
	Plat10	9				
	P38	11				
	Plat6	9				
	Plat8	8				
	Plat7	11				
	Plat3	9				
	Plat4	8				
	Plat5	11				
Level 6	P13	9	15	8.87	0.2	4.08
	P14	9				
	P15	9				

Plat12	5
Plat1	8
Plat2	6
Plat9	11
Plat10	9
P35	11
Plat6	9
Plat8	8
Plat7	11
Plat3	9
Plat4	8
Plat5	11

Table 2 shows that exploring the tree from Level 1 to Level 6 the platforms variety increases from 1 to 15 as well as the average number of components per platform which increases from 1 to 8.87; while the platforms customization effort indicators decrease from 0.94 to 0.2 for PRI and from 21.97 to 4.08 for PCI.

The main results are in Figure 10 and Figure 11. In particular, Figure 10 shows the trend of the average number of components per platform (ACP) vs. PRI while Figure 11 shows the trend of platforms variety vs. PRI. The trends shown in these graphs indicate that as ACP and platforms variety increases PRI decreases. Similar trends are observed when plotting ACP and platforms variety vs. PCI.

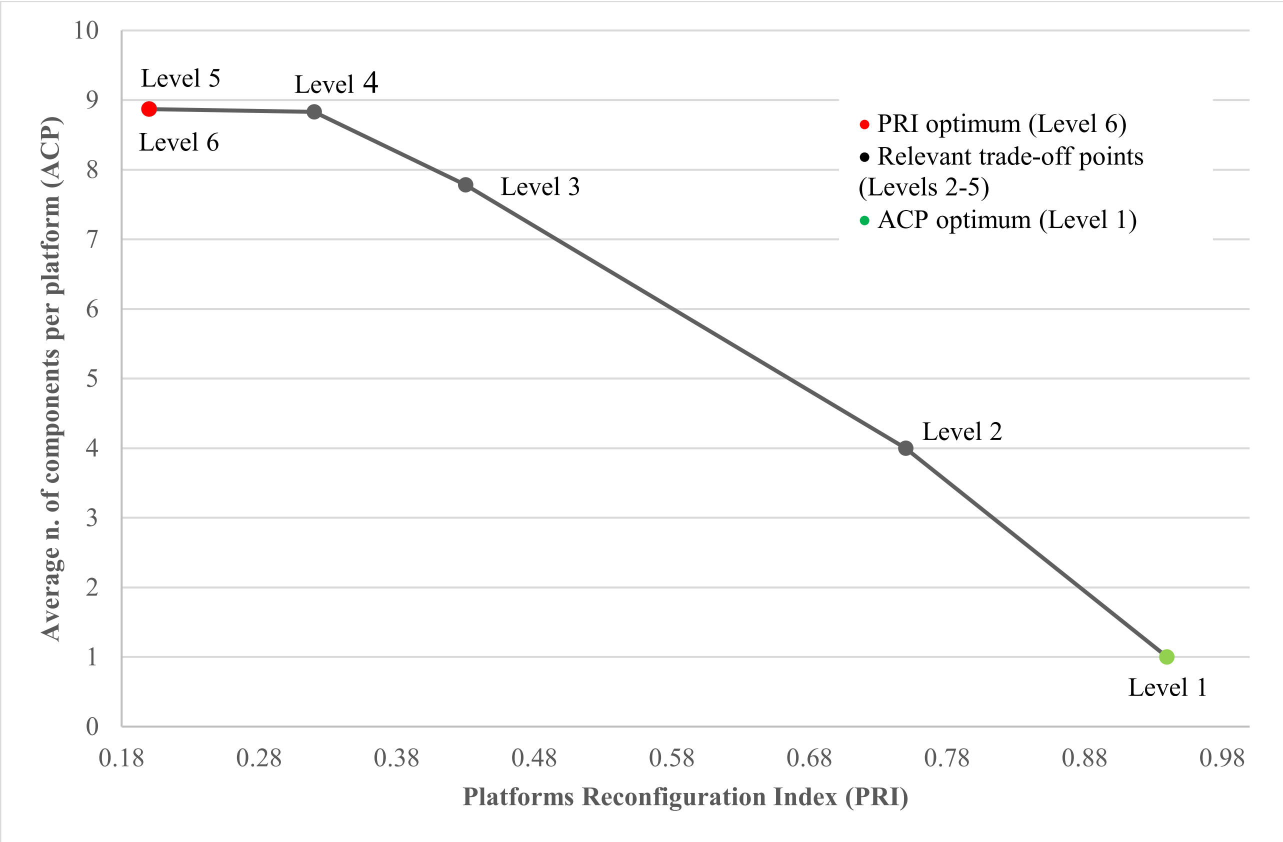

Figure 10: ACP vs. PRI trend

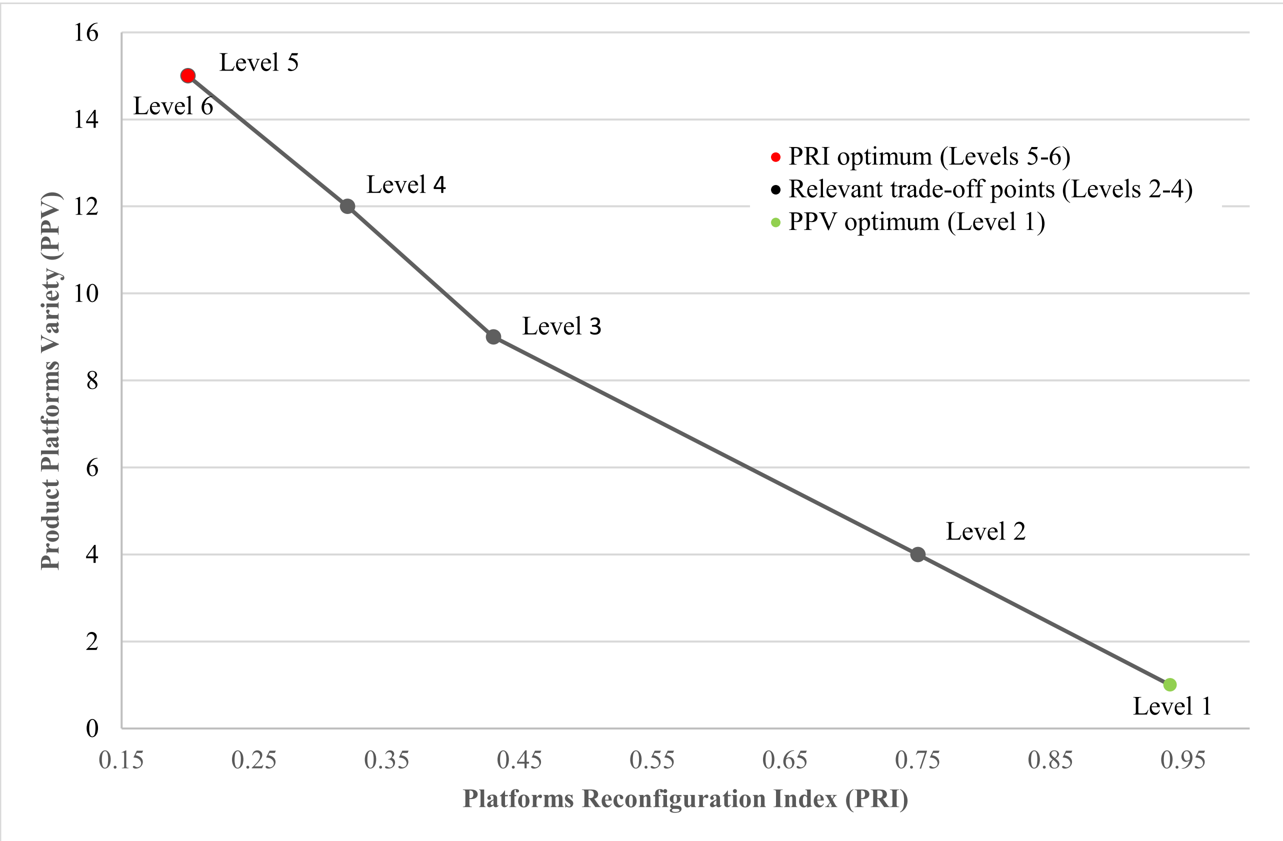

Figure 11: Platforms variety vs. PRI trend

2.3.4 Selection of best product platforms

The case company can select the platforms configuration that best meets its needs, having the values of platforms variety and platforms customization effort indices for each level of the phylogenetic network tree (Table 2). The considered case company aims at reducing the variety level, and consequently the inventory at the cost of acceptable increase of platforms customization effort in terms of number of the required assembly/disassembly tasks. For this reason, the platforms configuration from Level 6 is selected as a final solution. Figure 12 shows the product platforms (highlighted in grey) selected for mass production and storage prior to customization according to orders, as well as the assembly/disassembly relationships involved in subsequently producing each product reconfiguration.

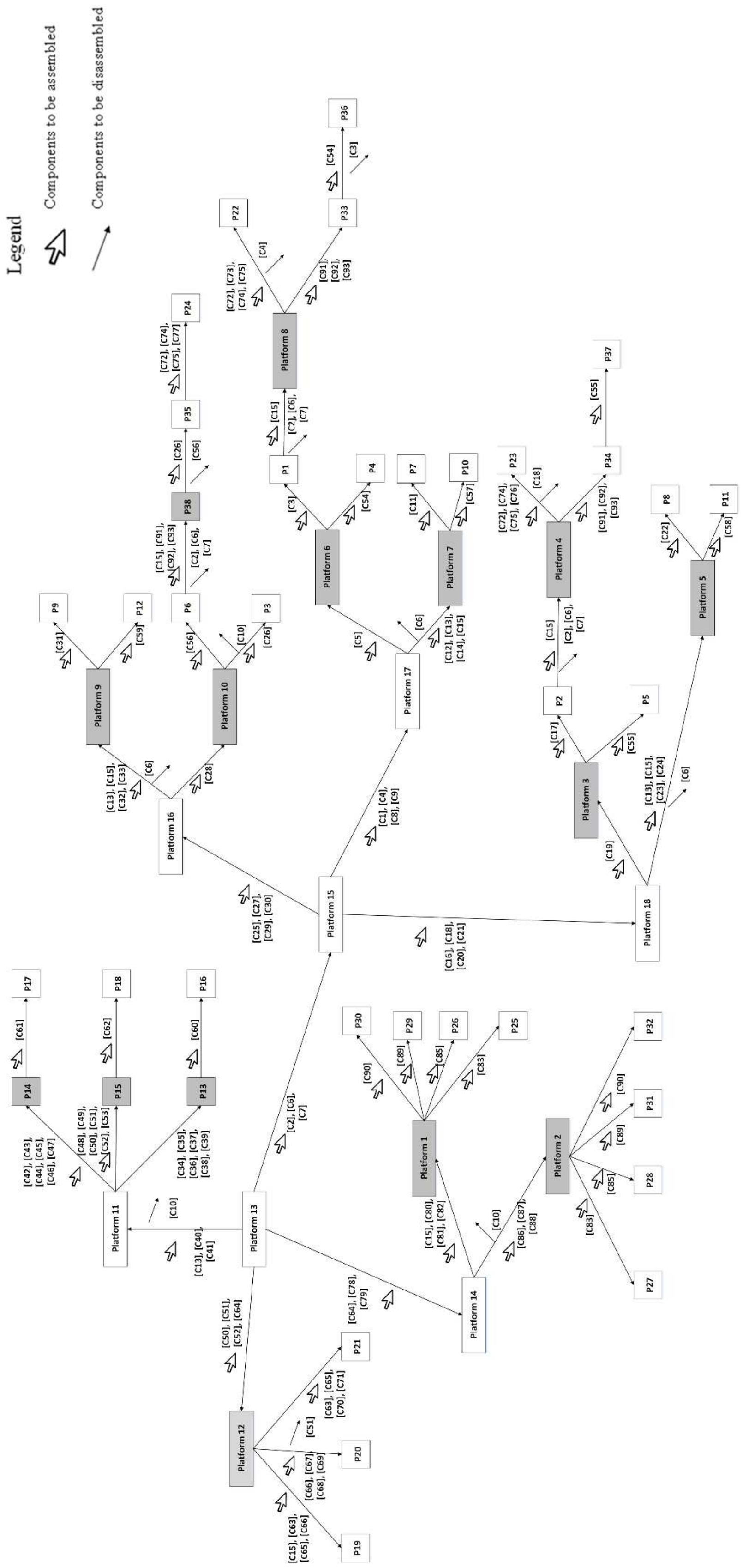

Figure 12: Final selection of product platforms

Compared to the current production strategy (MTS), in which the company stocks 38 types of valves, following the strategy suggested by the developed DSS, 15 valve platforms are selected for manufacture and storage leading to a reduction of 60.5% of product variety and consequently to significant savings in storage costs. The case company accepted an increase in platforms reconfiguration effort, represented by PRI and PCI indicators, of about 20% due to the platform reconfiguration required by the new production scenario compared to the MTS strategy. Individual final products were assembled and stocked in the company warehouse using the MTS strategy, while in the new proposed configuration based on DPD, only the platforms are stocked and reconfigured into the final products through assembly and disassembly operations as needed and shipped to customers, hence reducing warehouse storage and handling cost. The phylogenetic tree Level 6 selected by the case company corresponds to a value of PRI equal to 0.2, representing an increase of this index of about 20%. PRI and PCI indices are indicative of the cost of platform reconfiguration by assembly and disassembly. The selection of Level 6 leads to a slight increase of valves portfolio because the platforms themselves become new intermediate products that need to be managed. Nevertheless, the savings obtained in terms of storage costs and product variety reduction outweighed the reconfiguration effort increase.

The proposed DSS supports industrial companies in the transition towards the adoption of DPD by using product platforms providing detailed information about the platforms created in each level of reconfiguration together with the components involved in assembly and disassembly operations and the values of PRI and PCI indices, indicative of the cost of platform reconfiguration. Each level of the phylogenetic tree corresponds to a feasible DPD configuration and to a different trade-off between platform variety and platform reconfiguration effort, which is an effective tool to guide industrial companies in the selection of the most suitable DPD configuration.

2.4 Concluding Remarks

Dynamic market demands and changing customers' requirements and regulations are responsible for products variety proliferation. The use of product platforms is an effective strategy to manage the increasing variety and to delay products differentiation. This paper proposes an innovative decision support system (DSS) for product platforms design and selection to best manage the trade-off between platforms variety and number of assembly/disassembly tasks to be performed to transform a product platform into a product variant through platforms reconfiguration and customization efforts. The Median-Joining Phylogenetic Networks (MJPN) algorithm is used in the design and planning phases to define the number and composition of different platforms using both assembly and disassembly to customize the platforms into product variants as needed based on orders. The MJPN methodology is a widely used approach in biology but is relatively new in the manufacturing field. After the platforms design, the phylogenetic tree is decomposed into multiple levels to assist with platforms selection. New metrics to measure platforms customization effort by considering the required assembly/disassembly tasks, i.e. Platforms Reconfiguration Index (PRI), and the ease of assembly/disassembly factors, i.e. Platforms Customization Index (PCI), have been developed. They represent an important new contribution to the application of products platforms customization for managing variety in assembled products. In particular, such indices provide tools that support industrial companies in determining, for each product variant, whether it is better to adopt delay product differentiation (DPD) or assemble to order (ATO) strategy, and guide them in the selection of effective product platforms. A real case study of a large family of plastic valves is used to validate the proposed approach. The case studies found in literature involve small product families with limited number of products variants. In contrast, a family of thirty-eight (38) product variants is considered in this research. Each variant is composed of a combination of 9 to 14 components, for a total of 93 components. Results show that the developed DSS efficiently supports companies in the design and selection of effective platforms, leading to a reduction of the variety of assembled and stocked products of about 60.5% and to significant production and inventory efficiencies and cost savings. At the same time, the company accepted an increase of assembly/disassembly effort required for platforms customization by about 20% and an increase of valves portfolio, which is more than offset by the reduction in inventory cost. Using the MJPN and the assembly/disassembly modular product platforms offer the possibility to produce different products using more than one platform, providing more flexibility in production planning. The introduction of product platforms also helps companies achieve a more flexible response to the introduction of new products mix as well as increased adaptability to changing market demands. Future research deals with the inclusion of the annual demand data of the different product variants to consider its effect on the platforms design.

As stated in Chapter 1, while conventional manufacturing systems, such as DMSs, FMSs and CMSs, can be effectively used to mass-produce product platforms, advanced manufacturing solutions are needed to produce the remaining components necessary to reconfigure the product platforms into the final variants (Huang et al., 2019). Among Next Generation Manufacturing Systems (NGMSs), Reconfigurable Manufacturing Systems (RMSs) and Reconfigurable Assembly Systems (RASs), rise in the last few years to respond to the dynamic market changes. Next Chapters 2 and 3 investigate these systems and propose innovative methods supporting their design and management.

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Appendix A

Table A1: PRI values for Level 1 of the plastic valves phylogenetic tree

Reconfigurations	*Assembly tasks*	*NCApv*	*Disassembly tasks*	*NCDpv*	*NCVv*	*Strategy*	*PRIvp*
Plat 13 - P1	C1-C2-C3-C4-C5-C6-C7-C8-C9	9	-	0	10	DPD	0.9
Plat 13 - P2	C2-C6-C7-C16-C17-C18-C19-C20-C21	9	-	0	10	DPD	0.9
Plat 13 - P3	C2-C6-C7-C25-C26-C27-C28-C29-C30	9	C10	1	9	ATO	1
Plat 13 - P4	C1-C2-C4-C5-C6-C7-C8-C9-C54	9	-	0	10	DPD	0.9
Plat 13 - P5	C2-C6-C7-C16-C18-C19-C20-C21-C55	9	-	0	10	DPD	0.9
Plat 13 - P6	C2-C6-C7-C25-C27-C28-C29-C30-C56	9	-	0	10	DPD	0.9
Plat 13 - P7	C1-C2-C4-C7-C8-C9-C11-C12-C13-C14-C15	11	-	0	12	DPD	0.92
Plat 13 - P8	C2-C7-C13-C15-C16-C18-C20-C21-C22-C23-C24	11	-	0	12	DPD	0.92
Plat 13 - P9	C2-C7-C13-C15-C25-C27-C29-C30-C31-C32-C33	11	-	0	12	DPD	0.92
Plat 13 - P10	C1-C2-C4-C7-C8-C9-C12-C13-C14-C15-C57	11	-	0	12	DPD	0.92
Plat 13 - P11	C2-C7-C13-C15-C16-C18-C20-C21-C23-C24-C58	11	-	0	12	DPD	0.92
Plat 13 - P12	C2-C7-C13-C15-C25-C27-C29-C30-C32-C33-C59	11	-	0	12	DPD	0.92
Plat 13 - P13	C13-C34-C35-C36-C37-C38-C39-C40-C41	9	C10	1	9	ATO	1
Plat 13 - P14	C13-C40-C41-C42-C43-C44-C45-C46-C47	9	C10	1	9	ATO	1
Plat 13 - P15	C13-C40-C41-C48-C49-C50-C51-C52-C53	9	C10	1	9	ATO	1
Plat 13 - P16	C13-C34-C35-C36-C37-C38-C39-C40-C41-C60	10	C10	1	10	ATO	1
Plat 13 - P17	C13-C40-C41-C42-C43-C44-C45-C46-C47-C61	10	C10	1	10	ATO	1
Plat 13 - P18	C13-C40-C41-C48-C49-C50-C51-C52-C53-C62	10	C10	1	10	ATO	1
Plat 13 - P19	C15-C50-C51-C52-C63-C64-C65-C66	8	-	0	9	DPD	0.89
Plat 13 - P20	C50-C52-C64-C66-C67-C68-C69	7	-	0	8	DPD	0.88
Plat 13 - P21	C50-C51-C52-C63-C64-C65-C70-C71	8	-	0	9	DPD	0.89
Plat 13 - P22	C1-C3-C5-C8-C9-C15-C72-C74-C75-C77	10	-	0	11	DPD	0.91
Plat 13 - P23	C15-C16-C17-C19-C20-C21-C72-C74-C75-C76	10	-	0	11	DPD	0.91
Plat 13 - P24	C15-C25-C26-C27-C28-C29-C30-C72-C74-C75-C77-C91-C92-C93	14	-	0	14	ATO	1

Plat 13 - P25	C15-C64-C78-C79-C80-C81-C82-C83	8	-	0	9	DPD	0.89
Plat 13 - P26	C15-C64-C78-C79-C80-C81-C82-C85	8	-	0	9	DPD	0.89
Plat 13 - P27	C64-C78-C79-C83-C86-C87-C88	7	C10	1	7	ATO	1
Plat 13 - P28	C64-C78-C79-C85-C86-C87-C88	7	C10	1	7	ATO	1
Plat 13 - P29	C15-C64-C78-C79-C80-C81-C82-C89	8	-	0	9	DPD	0.89
Plat 13 - P30	C15-C64-C78-C79-C80-C81-C82-C90	8	-	0	9	DPD	0.89
Plat 13 - P31	C64-C78-C79-C86-C87-C88-C89	7	C10	1	7	ATO	1
Plat 13 - P32	C64-C78-C79-C86-C87-C88-C90	7	C10	1	7	ATO	1
Plat 13 - P33	C1-C3-C4-C5-C8-C9-C15-C91-C92-C93	10	-	0	11	DPD	0.91
Plat 13 - P34	C15-C16-C17-C18-C19-C20-C21-C91-C92-C93	10	-	0	11	DPD	0.91
Plat 13 - P35	C15-C25-C26-C27-C28-C29-C30-C91-C92-C93	10	-	0	11	DPD	0.91
Plat 13 - P36	C1-C4-C5-C8-C9-C15-C54-C91-C92-C93	10	-	0	11	DPD	0.91
Plat 13 - P37	C15-C16-C17-C18-C19-C20-C21-C55-C91-C92-C93	11	-	0	11	ATO	1
Plat 13 - P38	C15-C25-C27-C28-C29-C30-C56-C91-C92-C93	10	-	0	11	DPD	0.91
						PRI	***0.94***
Product platform variety							***1***

Table A2: PCI values for Level 1 of the plastic valves phylogenetic tree

Reconfigurations	*Assembly tasks*	*MH*	*I*	*sumACIcpv*	*Disassembly tasks*	*sumDCIcpv*	*PCIvp*
Plat 13 - P1	C1-C2-C3-C4-C5-C6-C7-C8-C9	00	06	54	-	0	54
Plat 13 - P2	C2-C6-C7-C16-C17-C18-C19-C20-C21	00	06	54	-	0	54
Plat 13 - P3	C2-C6-C7-C25-C26-C27-C28-C29-C30	00	06	54	C10	6.12	60.12
Plat 13 - P4	C1-C2-C4-C5-C6-C7-C8-C9-C54	00	06	54	-	0	54
Plat 13 - P5	C2-C6-C7-C16-C18-C19-C20-C21-C55	00	06	54	-	0	54
Plat 13 - P6	C2-C6-C7-C25-C27-C28-C29-C30-C56	00	06	54	-	0	54
Plat 13 - P7	C1-C2-C4-C7-C8-C9-C11-C12-C13-C14-C15	00	06	66	-	0	66
Plat 13 - P8	C2-C7-C13-C15-C16-C18-C20-C21-C22-C23-C24	00	06	66	-	0	66
Plat 13 - P9	C2-C7-C13-C15-C25-C27-C29-C30-C31-C32-C33	00	06	66	-	0	66

Plat 13 - P10	C1-C2-C4-C7-C8-C9-C12-C13-C14-C15-C57	00	06	66	-	0	66
Plat 13 - P11	C2-C7-C13-C15-C16-C18-C20-C21-C23-C24-C58	00	06	66	-	0	66
Plat 13 - P12	C2-C7-C13-C15-C25-C27-C29-C30-C32-C33-C59	00	06	66	-	0	66
Plat 13 - P13	C13-C34-C35-C36-C37-C38-C39-C40-C41	00	06	54	C10	6.12	60.12
Plat 13 - P14	C13-C40-C41-C42-C43-C44-C45-C46-C47	00	06	54	C10	6.12	60.12
Plat 13 - P15	C13-C40-C41-C48-C49-C50-C51-C52-C53	00	06	54	C10	6.12	60.12
Plat 13 - P16	C13-C34-C35-C36-C37-C38-C39-C40-C41-C60	00	06	60	C10	6.12	66.12
Plat 13 - P17	C13-C40-C41-C42-C43-C44-C45-C46-C47-C61	00	06	60	C10	6.12	66.12
Plat 13 - P18	C13-C40-C41-C48-C49-C50-C51-C52-C53-C62	00	06	60	C10	6.12	66.12
Plat 13 - P19	C15-C50-C51-C52-C63-C64-C65-C66	00	06	48	-	0	48
Plat 13 - P20	C50-C52-C64-C66-C67-C68-C69	00	06	42	-	0	42
Plat 13 - P21	C50-C51-C52-C63-C64-C65-C70-C71	00	06	48	-	0	48
Plat 13 - P22	C1-C3-C5-C8-C9-C15-C72-C74-C75-C77	00	06	60	-	0	60
Plat 13 - P23	C15-C16-C17-C19-C20-C21-C72-C74-C75-C76	00	06	60	-	0	60
Plat 13 - P24	C15-C25-C26-C27-C28-C29-C30-C72-C74-C75-C77-C91-C92-C93	00	06	84	-	0	84
Plat 13 - P25	C15-C64-C78-C79-C80-C81-C82-C83	00	06	48	-	0	48
Plat 13 - P26	C15-C64-C78-C79-C80-C81-C82-C85	00	06	48	-	0	48
Plat 13 - P27	C64-C78-C79-C83-C86-C87-C88	00	06	42	C10	6.12	48.12
Plat 13 - P28	C64-C78-C79-C85-C86-C87-C88	00	06	42	C10	6.12	48.12
Plat 13 - P29	C15-C64-C78-C79-C80-C81-C82-C89	00	06	48	-	0	48
Plat 13 - P30	C15-C64-C78-C79-C80-C81-C82-C90	00	06	48	-	0	48
Plat 13 - P31	C64-C78-C79-C86-C87-C88-C89	00	06	42	C10	6.12	48.12
Plat 13 - P32	C64-C78-C79-C86-C87-C88-C90	00	06	42	C10	6.12	48.12
Plat 13 - P33	C1-C3-C4-C5-C8-C9-C15-C91-C92-C93	00	06	60	-	0	60
Plat 13 - P34	C15-C16-C17-C18-C19-C20-C21-C91-C92-C93	00	06	60	-	0	60

Plat 13 - P35	C15-C25-C26-C27-C28-C29-C30-C91-C92-C93	00	06	60	-	0	60
Plat 13 - P36	C1-C4-C5-C8-C9-C15-C54-C91-C92-C93	00	06	60	-	0	60
Plat 13 - P37	C15-C16-C17-C18-C19-C20-C21-C55-C91-C92-C93	00	06	66	-	0	66
Plat 13 - P38	C15-C25-C27-C28-C29-C30-C56-C91-C92-C93	00	06	60	-	0	60
						PCI	***21.97***

MH = Material Handling two-digit code; I = Insertion two-digits code.

3 DESIGN AND MANAGEMENT OF RECONFIGURABLE MANUFACTURING SYSTEMS

This chapter addresses the *RQ. 2* and aims at defining models and tools supporting the design and management of a class of reconfigurable systems, called Cellular Reconfigurable Manufacturing Systems (CRMSs), which emerge in the last years as effective solutions able to overcoming the weaknesses of conventional CMSs matching, at the same time, the dynamics of modern market. Deep attention is paid at the transition from the Dynamic Cell Formation Problem (DCFP), which proposes machine duplications and relocations among the manufacturing cells as a solution to cope with variation in part mix and demand, to CRMSs, which propose machine reconfiguration to enhance machine capabilities to process a wider range of production tasks. Finally, implications of such systems on safety, ergonomics and human factors are analyzed. The content is based on the following research papers: (1) Bortolini, M., Ferrari, E., Galizia, F. G., Mora, C., Pilati, F. (2019). Optimal redesign of cellular flexible and reconfigurable manufacturing systems, *Procedia CIRP*, 81, 1435-1440, (2) Bortolini, M., Galizia, F. G., Mora, C. (2018). Reconfigurable manufacturing systems: literature review and research trend, *Journal of Manufacturing Systems*, 49, 93-106, (3) Bortolini, M., Galizia, F. G., Mora, C. (2019). Dynamic design and management of reconfigurable manufacturing systems, *Procedia Manufacturing*, 33, 67-74, (4) Bortolini, M., Galizia, F. G., Mora, C., Pilati, F. (2019). Reconfigurability in cellular manufacturing systems: a design model and multi-scenario analysis, *The International Journal of Advanced Manufacturing*, in press, (5) Bortolini, M., Botti, L., Galizia, F. G., Mora, C. (2019). Safety, ergonomics and human factors in reconfigurable manufacturing systems, In: *Reconfigurable Manufacturing Systems: from design to implementation*, Springer Series in Advanced Manufacturing, in press.

Within the current industrial environment, manufacturing companies are facing radical changes forcing to improve their standard in product and process design and management. High flexibility, dynamic market demand, increasing customisation, high-quality products, flexible batches and short product life cycles are among the key factors driving the transition from the traditional manufacturing systems to the so-called Next Generation Manufacturing Systems (NGMSs) (Mehrabi et al., 2000, Mehrabi et al., 2002, Molina et al., 2005, Hasan et al., 2014). In this context, the traditionally most adopted production systems such as Dedicated Manufacturing Systems (DMSs), Flexible Manufacturing Systems (FMSs) and Cellular Manufacturing Systems (CMSs) show increasing limits in adapting themselves to the most recent market features. Focusing on CMSs, within the last few decades, Cellular Manufacturing (CM) has been one of the most successful strategies adopted by industrial companies to cope with the challenges of modern global competitive environment (Nsakanda et al., 2006). In conventional CMSs similar parts or products are grouped to create families, while the required working machines compose manufacturing cells with the aim of reducing production time, setups, work-in-process, increasing quality and the system productivity (Singh, 1993, Wemmerlov and Johnson, 1997, Defersha and Chen, 2005). However, in conventional CMSs, once machine cells are designed, the physical relocation of the facilities included in each cell in response to new production requirements becomes difficult. To overcome such and other weaknesses, the literature firstly introduces the so-called Dynamic Cell Formation Problem (DCFP) aims at coping with variation in part mix and demand implementing machine relocations and duplications among the available manufacturing cells. Such actions significantly contribute to the reduction of the intercellular flows, even if, at the same time, lead to an increase of the investment costs, i.e. direct costs, caused by the purchasing of the duplicated machines. To overcome this deficiency, current literature proposes the adoption of the emerging principles of reconfigurability in manufacturing. Thus, Reconfigurable Manufacturing Systems (RMSs) and, in particular, Cellular Reconfigurable Manufacturing Systems (CRMS) are rising as innovative manufacturing systems in which machine modification is performed instead of their relocation and/or duplication with the aim to enhance machine capabilities to process a wider range of production tasks. Starting from this background, this chapter firstly explores the DCFP proposing in Section 3.1 a mathematical model supporting the redesign of CMSs through machine relocations/duplications. Afterwards, following the recent shift toward the reconfigurable manufacturing paradigm, the emerging concept of reconfigurability is fully revised in Section 3.2 while a design model supporting the optimal design and management of CRMSs best-managing the trade-off between inbound logistics and machine reconfiguration is presented in Section 3.3. Finally, Section 3.4 proposes a new methodological framework integrating safety, ergonomics and human factors in CRMSs.

3.1 THE DYNAMIC CELL FORMATION PROBLEM IN CMS DESIGN

Within the CM philosophy, Group Technology (GT) aims at identifying parts characterized by similar features and grouping them together in families to benefits from their similarities in manufacturing and design (Selim et al., 1998). The fundamental idea of GT is to ease the planning and control phases of a manufacturing system decomposing it into several sub-systems (Mohammadi and Forghani, 2017). CM is an application of GT in which similar parts are grouped together in part families and the corresponding machines into machine cells getting significant reductions in setup times, lead times and work-in-process (WIP) (Singh, 1993, Wemmerlov and Johnson, 1997, Defersa and Chen, 2005). To reach the above-mentioned benefits, Cellular Manufacturing Systems (CMSs) aim at joining the advantages of both job shops and flow shops. Job shops are suitable for the manufacturing of a wide variety of products in small lot sizes. In such systems, machines performing similar functions are located in the same department so that parts requiring different machine types for the performance of their operations need to travel within the different departments. This system organization generally leads to increased amount of material handling and WIP inventories. On the opposite, flow shops are designed to produce high volumes of products at a competitive cost but they require high investment for purchasing machines. This system performs better than the previous one in terms of material handling, WIP and setup times because of the machines are located in the production lines according to the product work cycles (Mohammadi and Forghani, 2017). Since both job and flow shops cannot simultaneously provide efficiency and flexibility goals to the product variety, CMSs emerged to achieve these requirements. The aim of this section is to present an original procedure based on operational research (OR) for the redesign of cellular production environments following the DCFP, which proposes both machine relocations and duplications as solutions to reduce intercellular flows. Past and current literature proves that these strategies could lead to relevant benefits for an effective working of CMSs but few studies still exist.

According to these goals, the reminder of this Section is organized as follows: Section 3.1.1 revises the relevant literature on the topic. Section 3.1.2 introduces the proposed mathematical model while Section 3.1.3 presents a case study, based on an instance inspired from the literature, and the results discussion. Finally, Section 3.1.4 presents key outcomes and final remarks.

3.1.1 Literature review

This section is organized into two parts. The former explores models and tools addressing the cell formation (CF) problem in CMSs design while the latter revises the relevant contributions considering the opportunity to relocating and/or duplicating machines in cellular manufacturing environments.

3.1.1.1 The cell formation problem in CMSs design

In CMSs, the CF problem is the crucial step to implement. It deals with models and tools to grouping of parts in families and machines in cells (Mehdizadeh and Rahimi, 2016). In the last decades, the literature proposed a wide set of contributions facing the CF problem with different strategies and methodologies, e.g. heuristic, metaheuristic and hybrid algorithms. Chen and Srivastava (1994) proposed a programming quadratic model for the CF problem maximizing the sum of machine similarities within cells by using a simulated annealing-based algorithm. Boctor (1991) defined a mathematical model to minimize the number of exceptional elements (EEs) solved with a simulated annealing algorithm. Xambre and Vilarinho (2003) proposed a mathematical programming model addressing the CF problem with multiple identical machines minimizing the intercellular flow and using a simulated annealing procedure to solve it. A wide but still limited group of researchers considers the existence of alternative process routings for the production of parts. Won and Kim (1997) considered the machine-part clustering problem in GT in which parts are characterized by multiple routings and developed an algorithm based on multiple clustering criteria that minimize the number of EEs. Akturk and Turkcan (2000) proposed an algorithm to solving the integrated part-family and machine-cell formation problem maximizing the efficiency of both individual cells and the overall cellular systems economic performances. Jeon and Leep (2006) developed a methodology to form manufacturing cells introducing a new similarity coefficient based on the number of alternative routes during demand changes within multiple time periods. Kao and Lin (2012) defined a discrete particle swarm optimization (PSO) approach to face the CF problem in presence of alternative process routings, minimizing the number of exceptional parts outside the machine cells and comparing the results to those obtained by applying simulated annealing and tabu search based algorithms. Chang et al. (2013) considered three relevant aspects in designing CMSs, i.e. cell formation, cell layout and intracellular machine sequence and proposed a mathematical model to integrate such issues considering alternative process routings, operation sequences, and production volumes. Mohammadi and Forghani (2014) proposed an integrated approach to designing CMSs considering both inter- and intra-cell layouts. The Authors included various production factors such as alternative process routings, part demands and operation sequences in the mathematical formulation, with the overall objective to minimize the total manufacturing costs. The reviewed studies rarely proposed mathematical models and methods solved by applying heuristic and metaheuristic techniques. Among these, some researchers apply hybrid techniques to solve the CMS design problem. The main ability of these methods is to join together the strengths of different techniques. Caux et al. (2000) defined an algorithm for the CF problem to minimize the inter-cell traffic. A hybrid methodology integrating simulated annealing for the CF and branch & bound for the routing selection is used for the model resolution. Goncalves and Resende (2004) introduced a new hybrid approach to forming machine cells and product families based on local search and heuristic algorithms with the overall goal to maximize the grouping efficacy. Chiang and Lee (2004) addressed the joint problem of manufacturing cell formation and its layout assignment, minimizing the intercell flow cost under the cell size constraint. This model is solved by combining a simulated annealing algorithm augmented with a dynamic programming. Saghafian and Akbari Jokar (2009) proposed a new integrated view of manufacturing CF and both inter- and intra-cell layout problems and developed a hybrid method based on dynamic programming, simulated annealing and genetic operators to minimize the total inter- and intra-cell handling cost. Nsakanda et al. (2006) integrated the CF problem, the machine allocation problem and the part routing problem in designing CMSs, defining a solution methodology based on genetic algorithm and large-scale optimization techniques.

3.1.1.2 Benefits of machine relocations/duplications in CMSs

Despite the literature focusing on the design and management of CMSs is wide, few studies explore the convenience to simultaneously relocate and/or duplicate a machine in a manufacturing cell as introduced by Selim et al. (1998) and Wu (1998). They demonstrated that machine duplication significantly contributes to the reduction of intercellular flows increasing, at the same time, the interdependence among machine cells. Logendran and Ramakrishna (1997) defined a model to duplicating bottleneck machines and subcontracting bottleneck parts under budgetary restrictions in CM systems. Irani and Huang [25] defined practical strategies for machine duplication in cellular manufacturing layouts. Tavakkoli-Moghaddam et al. (2007) presented a fuzzy linear programming model for the design of CMSs by considering fuzzy part demands and changeable product mix as well as alternative process plans for part type and the possibility to duplicate machines. Bortolini et al. (2011) introduced a hybrid procedure based on cluster analysis and integer linear programming techniques to solving the CF problem allowing the possibility of duplicating machines. Mohammadi and Forghani (2017) proposed a bi-objective model addressing the CF problem considering alternative process routings and machine duplications. The proposed formulation aims at minimizing the total dissimilarity among the parts and the total investments needed for the acquisition of the machines.

Following this research stream, next Section 3.1.2 presents the proposed optimization model for cellular production environments redesign in which both machines relocations and duplications are allowed.

3.1.2 A mathematical model for cellular production environment redesign

According to the adopted research approach based on OR, an optimization model for cellular production environment redesign is proposed. The model belongs to the so-called improvement models because, starting from an initial configuration, it evaluates the possibility to relocate and/or duplicate machine types in other manufacturing cells. In particular, the relocation and the redundancy of a machine type in one or more cells can significantly decrease the total number of intercellular flows and consequently the total indirect costs. In contrast, in case of duplications, adding resources to the production environment makes the manufacturing system more complex and this decision generally implies an increase of investments costs. An effective trade-off is of strong interest.

In the following, an optimization model evaluates the best configuration of machine cells in the cellular manufacturing environment including machine relocations and duplications. The model is developed to avoid non-linearity and to guarantee solvability in a reasonable time. The model nomenclature and formulation is in the following.

Indices

i	Index for parts $i = 1, \dots, M$
j, j_1, j_2	Index for cells $j, j_1, j_2 = 1, \dots, N$

k, k_1 Index for machine types $k, k_1 = 1, \dots, P$

o, o_1 Index for operations in part work cycle $o, o_1 = 1, \dots, O_i$

Parameters

C_{kj} Number of machines type *k* assigned to cell *j* in the initial configuration [# items]

V_{ik}^{o} 1 if part *i* requires machine *k* for operation *o*; 0 otherwise

q_i Planned production volume during a predefined period of time for part *i* [pcs/months]

t_i^o Processing time for operation *o* in part *i* work cycle [minutes/pc]

Z_i Required number of trips per part *i* [# trips]

$€_k^{mach}$ Duplication cost of machine [€/machine]

$€_k^{reloc}$ Relocation cost of machine [€/machine]

$€_{jj_1}^{flux}$ Unit intercellular flow cost [€/machine]

τ Available time for machines [minutes/machine]

Decision variables

R_{kj} Number of machines type *k* in cell *j* after relocation/duplication

RD_{kj} Total number of relocations and duplications of machine type *k* in cell *j*

$F_{ijj_1}^{o}$ 1 if part *i* moves from cell *j* to cell j_1 after operation *o*; 0 otherwise

$o = 1, \dots, O_i - 1$

3.1.2.1 *Model formulation*

The analytic formulation of the proposed model is in the following.

$\min \psi = \sum_{k=1}^{P} €_k^{reloc} \cdot \sum_{j=1}^{N} RD_{kj} +$

$$\sum_{k=1}^{P}(€_k^{mach} - €_k^{reloc}) \cdot \sum_{j=1}^{N} R_{kj} - \sum_{j=1}^{N} C_{kj} + \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{o=1}^{O_i-1} €_{jj_1}^{flux} \cdot F_{ijj_1o} \cdot Z_i \quad (1)$$

(1) minimizes the total cost as the sum of the costs generated by relocations of machines (first term in Eq. 1), by purchasing of new machines, i.e. duplication costs (second term in Eq. 1) and by intercellular flows (third term in Eq. 1).

The model is subject to the following feasibility constraints, which reproduce real industrial contexts:

$$\sum_{j=1}^{N}\sum_{j_1=1}^{N} F_{ijj_1o} = 1 \qquad i = 1, \dots, M; \quad o = 1, \dots, O_i - 1 \qquad (2)$$

$$\sum_{j_1=1}^{N} F_{ij_1jo} = \sum_{j_1=1}^{N} F_{ijj_1o+1} \qquad i = 1, \dots, M; \quad j = 1, \dots, N; \quad o = 1, \dots, O_i - 2 \qquad (3)$$

$$\sum_{i=1}^{M}\sum_{j_1=1}^{N}\sum_{o=1}^{O_i-1} F_{ijj_1o} \cdot V_{ik}^{o} \cdot q_i \cdot t_i^{o} + \sum_{i=1}^{M}\sum_{j_1=1}^{N} F_{ij_1jO_i-1} \cdot V_{ik}^{O_i} \cdot q_i \cdot t_i^{O_i} \leq R_{kj} \cdot \tau \qquad k = 1, \dots, P; \quad j = 1, \dots, N \qquad (4)$$

$$RD_{kj} \geq R_{kj} - C_{kj} \qquad \forall k, j \qquad (5)$$

$$R_{kj}, RD_{kj} \geq 0, \text{integer} \qquad \forall k, j \qquad (6)$$

$$F_{ijj_1o} \text{ binary} \qquad \forall i, j, j_1, o \qquad (7)$$

Constraints (2) and (3) guarantee the continuity of parts flow within the manufacturing system. (4) forces the manufacturing of the part production volumes to be completed within the available machine uptime. (5) sets the auxiliary variable $\boldsymbol{RD_{kj}}$ as the difference between the number of machines *k* in cell *j* after the relocation/duplication and the number of that machines in the initial configuration. (6)-(7) give consistence to the decision variables.

3.1.3 Model application

3.1.3.1 Case study description

The proposed model is applied to a case study made of an instance of the CF problem introduced by Gupta and Seifoddini (1990), characterized by a 43 x 16 matrix (number of parts x number of machines). Furthermore, a set of eight different operations is available to manufacture the parts and five machine cells are available for machine assignment. A multi-scenario analysis is performed to assess how the results change changing the relationship between duplication and intercellular flow costs. The input data with reference to the parts and their work cycles are in Table B1 included in Appendix B. Table 3 shows the initial configuration, i.e. the machine-cell assignment and, for each machine type, the number of machines allocated to each manufacturing cell.

The model is coded in AMPL language and processed adopting Gurobi Optimizer© v.4.0.1.0 solver. An Intel® CoreTM i7 CPU @ 2.40GHz and 8.0GB RAM workstation is used. The solving time is approximately of about 20 seconds per scenario.

Table 3: Initial cellular manufacturing configuration

	C1	C2	C3	C4	C5
m1		1			
m2		3			
m3	2				
m4				7	
m5				7	
m6			11		
m7			1		
m8				14	
m9		5			
m10			7		

m11					10
m12					3
m13					1
m14	2				
m15				3	
m16		5			

3.1.3.2 *Results and discussion*

The multi-scenario analysis is carried out to test the model varying some of the key input parameters. In particular, following the above-mentioned trade-off between the number of machine duplications and the number of intercellular flows, this analysis is performed changing, in each scenario, the relationship between the duplication and the intercellular flow costs. The aim is to find a configuration solution best-balancing the investments cost generated by purchasing of new machines and indirect costs generated by intercellular flows.

According to the industrial practice, a constant parameter $\mu = €_k^{mach}/€_k^{reloc}$ equal to 2.5 and a variable parameter $\xi = €_k^{mach}/€_{jj_1}^{flux}$, ranging in [25, 3200], are introduced. The μ value specifies that the cost of machine relocation is less than half the cost of the correspondent duplication. The parameter ξ specifies that, in the model objective function, a machine duplication, i.e. $€_k^{mach}$ cost, is equivalent to ξ intercellular flows, i.e. $€_{jj_1}^{flux}$cost. Globally, duplications become convenient if they allow to cut off more than ξ intercellular flows each.

The values of ξ parameter together with the main model results for each scenario are in Table 4 and Figure 13.

Table 4: Key model results in each scenario

Scenario Id.	ξ	Relocations [#]	Duplications [#]	Intercellular flows [#]	Objective function value [€]

S1	25	19	2	1	247
S2	50	19	2	1	487
S3	100	19	2	1	967
S4	200	15	2	6	1794
S5	400	15	1	9	3341
S6	800	9	1	17	5669
S7	1600	5	0	25	8145
S8	3200	0	0	55	9312

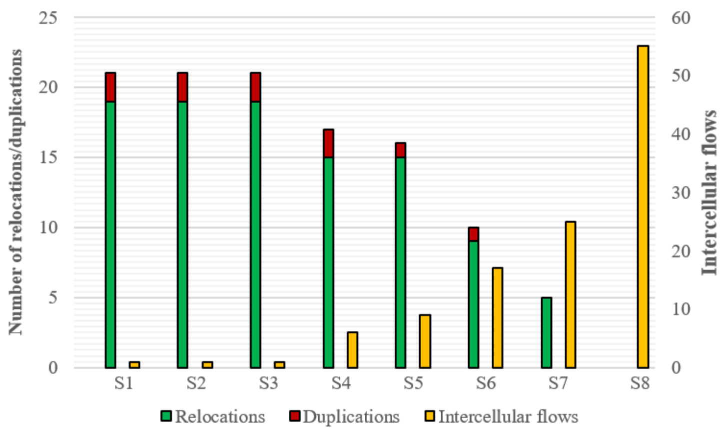

Figure 13: Multi-scenario analysis results

Results show that moving from S1 to S8, i.e. with the increase of parameter ξ, the number of intercellular flows increases while the number of machine relocations and duplications decreases. In particular, focusing on the first three scenarios, characterized by ξ values equal to 25, 50 and 100, respectively, the solutions present significant numbers of relocations compared to some duplications and very few intercellular flows. Such flows increase in S4 in which parameter ξ is equal to 200. Overall, in the presence of a machine purchasing cost, i.e. case of duplication, much greater than the unit intercellular flow cost, e.g. S8, the optimization process will promote the parts travelling among the machine cells. Instead, in presence of lower values of $\boldsymbol{\xi}$ parameter, the system shows the convenience of mixing the two strategies. The obtained results prove the existence of a significant trade-off between direct costs generated by machine relocations and duplications and indirect costs generated by intercellular flows, implying that the decision to relocate and/or duplicate a machine in a cellular manufacturing environment is a crucial opportunity for industrial companies to improve the economic and technical performances of their production systems.

3.1.4 Final remarks

Cellular Manufacturing Systems (CMSs) represent an effective alternative in production system organization adopted by several companies to guarantee higher levels of system flexibility and reactivity. To reach such benefits, similar parts are grouped in families and the corresponding machines into cells, addressing the cell formation (CF) problem. This study presents an optimal procedure for the redesign of mixed-model cellular manufacturing systems. An original integer linear programming model based on operational research (OR) is defined to evaluate the opportunity to relocate and/or duplicate machine types in manufacturing cells, best managing the trade-off between the direct costs generated by machine relocations and duplications and the indirect costs generated by intercellular flows. Starting from an initial cellular manufacturing configuration, the proposed model is applied to a case study made of an instance of the CF problem inspired from the literature. The main results show a decrease of the system intercellular flows without a high increase of the machine number in all the explored scenarios, getting a convenient and significant trade-off. Future research deals with the execution of experimental analysis to test the proposed model on different industrial and literature instances to compare the results obtained by adopting different problem settings. Moreover, as stated at the beginning of this chapter, RMSs are rising as effective systems able to overcome the deficiencies of CMSs. The main features of such systems are deeply described in the following.

3.2 RECONFIGURABLE MANUFACTURING SYSTEMS: LITERATURE REVIEW AND RESEARCH TREND

In modern industry, factors as high flexibility, dynamic market demand, increasing customisation, high-quality products, flexible batches and short product life cycles are among the key factors driving the transition from the traditional manufacturing systems to the so-called Next Generation Manufacturing Systems (NGMSs) (Mehrabi et al., 2000, Mehrabi et al., 2002, Molina et al., 2005, Hasan et al., 2014). Dedicated Manufacturing Systems (DMSs), Flexible Manufacturing Systems

(FMSs) and Cellular Manufacturing Systems (CMSs) show increasing limits in adapting themselves to the most recent market features. DMSs produce the company core products at a high production rate with low flexibility. Product features are supposed to be constant during the system lifetime and customisation is costly and difficult to implement (Koren and Shpitalni, 2010, Xing et al., 2006). FMSs consist of automated numerically controlled workstations connected through a proper handling system managed through a central control unit. The main advantage of FMSs is their flexibility in managing resources to manufacture a large variety of parts. However, in the most of the cases, the throughput of these systems is lower than for DMSs and the dedicate equipment increases the part full cost (Xing et al., 2006). CMSs overcome some limitations of the previous systems. They involve the use of multiple independent working cells dedicated to product families with similar processing requirements (Heragu, 1994). Despite this benefit, CMSs are designed to produce a specific set of products with stable demand level and sufficiently long lifecycle (Benjaafar et al., 2002).

To face the limits of the existing systems, NGMSs have to join high flexibility, reconfigurability and artificial intelligence properties to respond to the dynamic market changes (Molina et al., 2005). In 1999, Professor Koren firstly defines Reconfigurable Manufacturing System (RMS), as the NGMS '*designed at the outset for rapid change in structure, as well as in hardware and software components to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements*' (Koren et al., 1999, Koren, 2006).

Table 5 compares the expected features of DMSs, FMSs, CMSs and RMSs highlighting that RMSs aim at gathering the main advantages of traditional manufacturing systems combining flexibility to high throughput.

Table 5: Comparison among the main features of the existing manufacturing systems, adapted from (Koren and Shpitalni, 2010)

	DMS	FMS	CMS	RMS
Cost per part	Low	Reasonable	Medium	Medium
Demand	Stable	Variable	Stable	Variable
Flexibility	No	General	General	Customized
Machine structure	Fixed	Fixed	Fixed	Changeable
Product family formation	No	No	Yes	Yes
Productivity	Very high	Low	High	High
System structure	Fixed	Changeable	Fixed	Changeable
Variety	No	Wide	Wide	High

As a basis and background of the present review paper, Table 6 shows a list of existing reviews published in the field of RMSs, recently.

Table 6: Recent reviews on RMSs and target

Authors	Year	Target	Reference
Bi et al.	2008	Design methods for RMSs	Bi et al., 2008
ElMaraghy	2006	Analysis of flexibility in FMSs and RMSs	ElMaraghy, 2006
Rosio and Safsten	2013	Design methods for RMSs	Rosio and Safsten, 2013
Renzi et al.	2014	Artificial intelligence for the RMS design	Renzi et al., 2014
Huettemann et al.	2016	RMS-based assembly systems	Huettemann et al., 2015
Andersen et al.	2017	Design methods for RMSs	Andersen et al., 2017
Singh et al.	2017	Analysis of RMS key attributes	Singh et al., 2017

Table 6 shows that the target of the previous reviews is on specific aspects of RMSs, e.g. design methodologies, key attributes, etc. Connection among theory and practice, analytic models and applications are still missing and expected. To this purpose, this section presents an updated comprehensive literature review on the current state of the art on RMSs analysing a wide range of publications covering multiple areas and topics about RMS design, management and industrial application. The goal is to highlight the main research streams, the application areas and the methodologies supporting the RMS design and management. For these reasons, the main contributions and elements of innovation of this study in the field of RMSs are: (1) to propose a structured and updated literature review covering the range from 1999 to 2017, (2) to connect theory and practice about the design and management of such systems, (3) to cover multiple areas and topics of RMSs, e.g. design, management, scheduling, etc., and (4) to link reconfigurability to the *Industry 4.0* environment.

According to this goal, the reminder of this Section is organised as follows: the next Section 3.2.1 defines the RMSs and their features; Section 3.2.2 introduces the research approach, while Section 3.2.3 discusses the findings through a schematic of the RMS research perspectives. Finally, Section 3.2.4 concludes Section 3.3 with potential research directions and open questions and issues.

3.2.1 RMS features and market positioning

RMSs, as a recent class of manufacturing systems, have adjustable structure, both in the hardware and software architecture (Koren et al., 1999, Esmaeilian et al., 2016) and join the following six core features (Koren and Shpitalni, 2010, Bi et al., 2008, Setchi and Lagos, 2004):

- *Modularity*, the compartmentalisation of operational functions into units that can be manipulated among alternate production schemes for optimal arrangements;
- *Integrability*, the ability to connect modules rapidly and precisely by a set of mechanical, informative and control interfaces facilitating integration and communication;
- *Diagnosibility*, the system ability to self-reading its current state to detect and diagnose the root causes of product defects, quickly correcting them;
- *Convertibility*, the ability to easily transform the functionality of existing systems and machines to suit new production and market requirements;
- *Customisation*, the system and machine flexibility limited to a single product family, thereby obtaining customized flexibility;
- *Scalability*, the ability to modify easily the production capacity adding or removing resources and changing the system components.

These features make RMSs dynamic systems with the capacity and functionality to follow the market changes. Furthermore, RMSs, compared to the other manufacturing systems, allow producing a higher variety of customized products. Because of the link of the production system features to the market expectations is crucial, an extensive definition of RMS, including such aspect and extending the original definition provided by professor Koren in 1999 (Koren et al., 1999, Koren, 2006), is the following: *'RMS is a production system designed to match the dynamic market asking for high-quality products in variable quantities and at a reasonable cost. RMS has a changeable hardware and software structure allowing adjusting production capacity and functionality to combine high throughput rate, flexibility and cellular organisation pattern.'*

This definition emphasises the dynamism of RMSs and the link to both the market and the traditional manufacturing systems.

Research on RMSs increased in the recent past covering a wide set of research issues (Andersen et al., 2015). The most of the published papers presents methods to include some of the introduced features to existing manufacturing systems (Andersen et al., 2016) with lower attention in providing methodologies for best designing new RMSs. Furthermore, a structured design methodology to include the reconfigurability knowledge in the system design is expected (Rosio and Safsten, 2013, Andersen et al., 2017).

From the industrial perspective, few examples of RMS introduction into companies are available. Moreover, the current literature lacks of best practices driving industrial companies in the transition toward this new industrial paradigm. The greatest barrier toward the application of reconfigurable manufacturing is the resistance to change, especially by small and medium enterprises (SMEs). Such companies need to be trained to effectively adopt reconfigurable manufacturing. The so-called learning factories play a key role in linking academia to industry to spread the culture of innovation. In the last few years some prototypes of learning factories are established. They simulate small flexible and reconfigurable manufacturing and assembly systems with the purpose of practice and training for operators and students (Matt et al., 2015).

In parallel, reconfigurable manufacturing received great attention over the years by research councils located in many areas of the world through funding projects. Examples of relevant projects are *'Innovative manufacturing processes: flexible and reconfigurable manufacturing systems'* proposed by the Engineering and Physical Sciences Research Council (EPSRC) in 2012 and *'Mobile dual arm robotic workers with embedded cognition for hybrid and dynamically reconfigurable manufacturing systems'* proposed by the European Factories of the Future Research Association (EFFRA) in 2016. Within the context of European projects, relevant examples are the EU-funded projects *'Rapid reconfiguration of flexible production systems through capability-based adaptation, auto-configuration and integrated tools for production planning'* (RECAM) promoted in 2015 and *'Skill-based propagation of plug-and produce devices in reconfigurable manufacturing systems'* (SKILLPRO) promoted in 2016.

3.2.2 Research method

3.2.2.1 Location of the articles and paper database

The search of the articles is conducted by inserting search strings in scientific search engines, *Google Scholar* (scholar.google.com) and *Scopus* (scopus.com) mainly, to find relevant contributions on the analyzed topic. The analysis includes the most relevant literature contributions published between 1999 and 2017. In the phase of article screening, search strings include *'reconfigurable manufacturing system'*, *'RMS'* and *'reconfiguration'* as basic terms. After a first filtering of the articles based on their industrial oriented perspective, those published in ISI/Scopus international journals and indexed international conferences addressing the field of production planning and Supply Chain Management (SCM) are included in the review. A point of saturation is reached when articles continue to appear in the search. The selected articles are, further, categorised according to the specific electronic database (ED) they belong to. The main identified EDs are *Elsevier* (sciencedirect.com), *Taylor & Francis* (tandfonline.com), *Emerald* (emeraldinsight.com), *Springer* (springerlink.com), *IEEE* (ieeexplore.ieee.org) and *Inderscience* (inderscience.com).

The selected articles include 95 journal papers (73.64%), 5 book chapters (3.88%) and 29 indexed international conference papers (22.48%). These sources collect outstanding contributions reliable for the present review (Saunders et al., 2012). Globally, 129 articles are selected for this review. All of them deal with RMSs and related topics as reconfigurable machine systems and reconfigurable transportation systems. The next Section 3.2 provides more insights of the paper database.

3.2.2.2 Sources of publication and paper classification

The following graphs provide the paper database classification according to some relevant metrics. Figure 14 shows the temporal distribution of the selected papers, while Figure 15 and Figure 16 present the sources of publication and the EDs the papers belong to. In such last two figures, the most representative academic journals and the most representative EDs are shown, only.

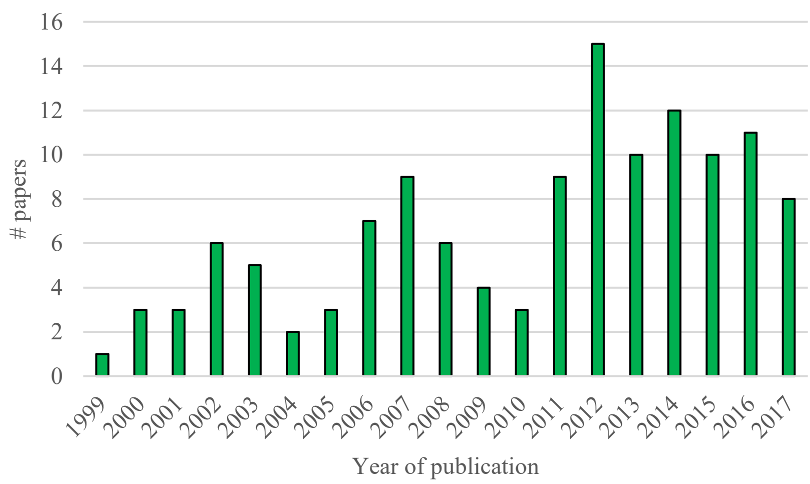

Figure 14: Paper database, classification per year of publication

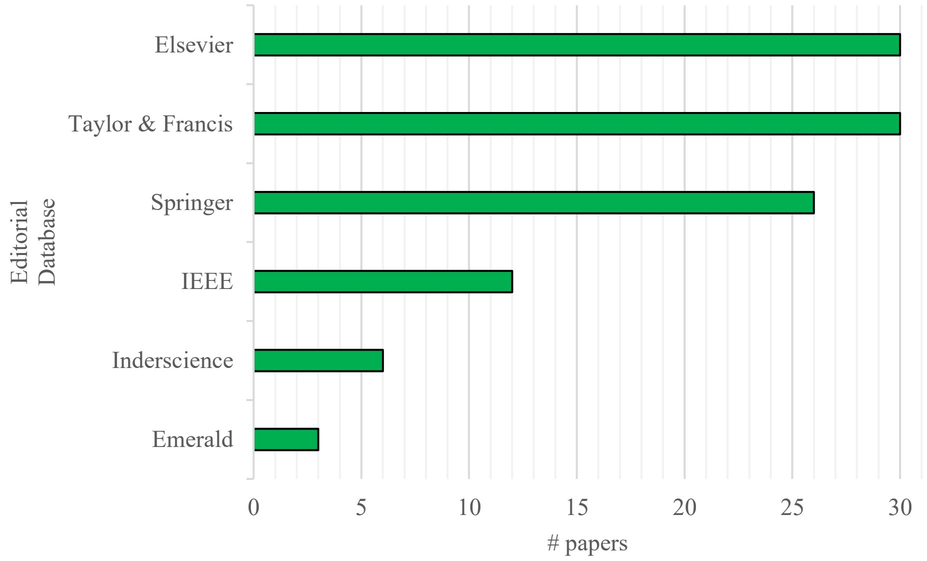

Figure 15: Paper database, classification per ED

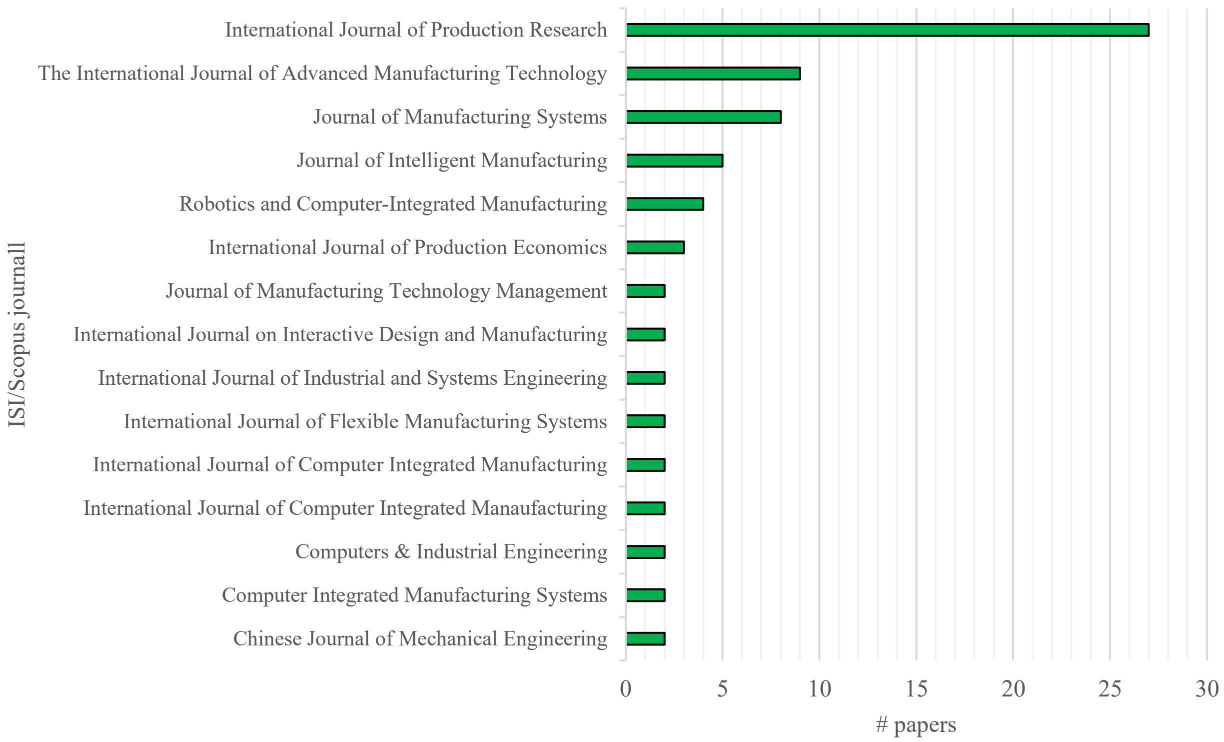

Figure 16: Paper database, classification per journal of publication

Up to the 60% of papers is published starting from 2010, proving the increasing relevance of RMSs in the recent past according to the rapid transformation of the market in the recent years. Furthermore, looking at the selected publication journals, the *International Journal of Production Research*, *The International Journal of Advanced Manufacturing Technology* and the *Journal of Manufacturing Systems* collect up to 46% of the considered publications and represent the privileged target to publish innovative papers about RMSs. In addition, Figure 16 indicates that RMS topic is cross-sectorial and fits to industrial engineering, economics, management science and production planning journal aim and scope.

3.2.3 Schematic of RMS research trend

The schematic of Figure 17 is of help to structure the present review. Following the research aim, the map is defined developing a categorisation of the articles included in the review according to their target topics. The articles are not partitioned among the identified research streams but each of them can belong to more than one stream due to its wider aim and scope.

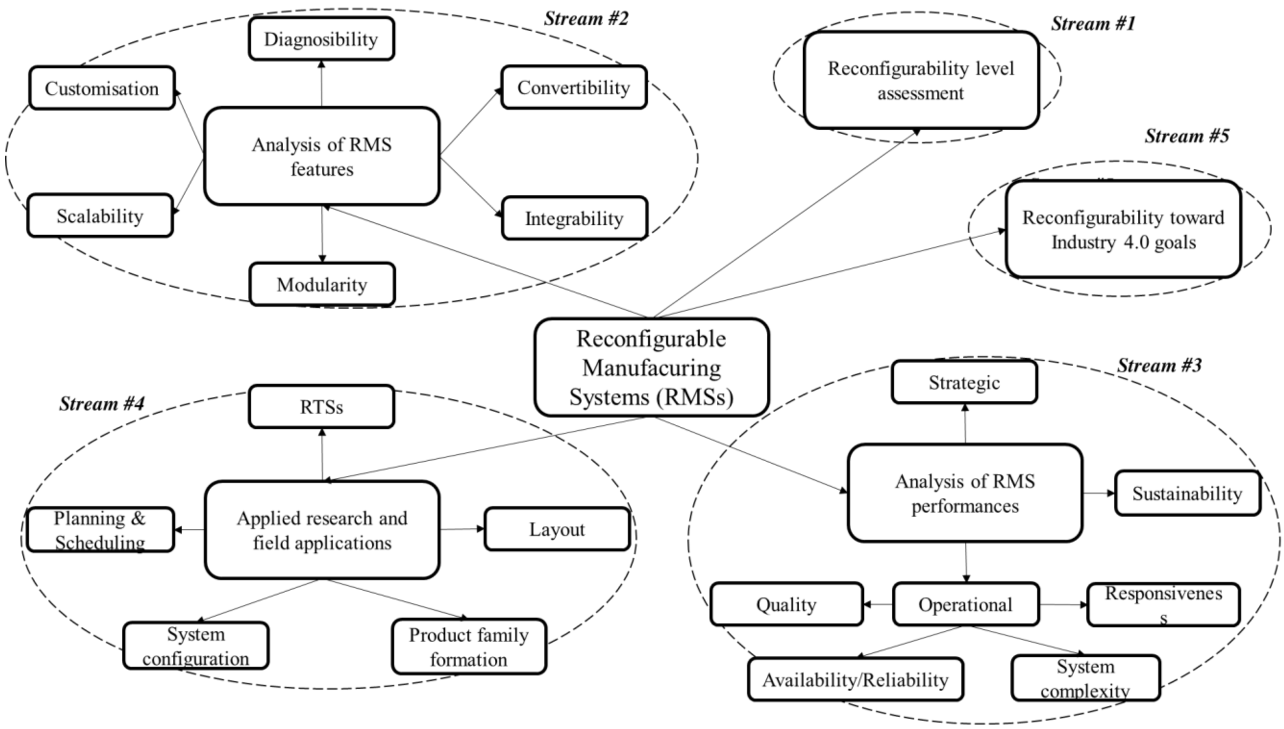

Figure 17: Schematic of RMS research perspectives

Five research streams allow collecting the focuses of the current research on RMSs.

Stream #1, Reconfigurability level assessment;

Stream #2, Analysis of RMS features, i.e. modularity, integrability, diagnosibility, convertibility, customisation, scalability;

Stream #3, Analysis of RMS performances;

Stream #4, Applied research and field applications;

Stream #5, Reconfigurability toward *Industry 4.0* goals.

Such streams are according to the main contents of the considered papers. Table 7 details the match between papers and streams, where a tick indicates that the paper in row addresses the stream in column. Multiple matches are possible indicating a multi-perspective focus and partial overlaps among the research streams. Furthermore, in Table 7 articles are listed per year, from past to date, allowing tracking the rising and evolution of each topic by the literature. The discussion of the streams is in the following of the present Section 3.2.3.

Table 7: Literature review: research trend and stream classification

Author(s)	Year	Stream #1	Stream #2	Stream #3	Stream #4	Stream #5
Xiaobo et al.	2000				✓	
Xiaobo et al.	2000				✓	
Son et al.	2001			✓		
Xiaobo et al.	2001				✓	
Xiaobo et al.	2001				✓	
Fan and Tan	2002				✓	
Maier-Speredelozzi and Hu	2002		✓		✓	
To and Ho	2002				✓	
Yigit et al.	2002		✓	✓		
Abdi and Labib	2003		✓		✓	
Bruccoleri et al.	2003			✓		
Maier-Speredelozzi et al.	2003			✓		
Yamada et al.	2003				✓	
Yigit and Allahverdi	2003			✓		
Abdi and Labib	2004				✓	

Abdi	2005	✓		✓
Spicer et al.	2005		✓	
Aiping and Nan	2006			✓
Bruccoleri et al.	2006		✓	
Deif and ElMaraghy	2006		✓	
Youssef and ElMaraghy	2006	✓		✓
Zhang et al.	2006	✓		
Alexopoulos et al.	2007		✓	
Deif and ElMaraghy	2007		✓	
Dou et al.	2007			✓
Galan et al.	2007			✓
Kuzgunkaya and ElMaraghy	2007	✓		
Pattanaik et al.	2007		✓	✓
Singh et al.	2007	✓	✓	
Wu et al.	2007			✓
Youssef and ElMaraghy	2007	✓		✓
ElMaraghy et al.	2008	✓		
Galan	2008			✓
Kuruvilla et al.	2008	✓		✓
Youssef and ElMaraghy	2008			✓
Zhang and Qiu	2008			✓
Abbasi and Houshmand	2009			✓
Abdi	2009	✓		
Bai et al.	2009			✓
Rehman and Subash Babu	2009			✓
Dou et al.	2010			✓
Rakesh et al.	2010			✓
Abbasi and Houshmand	2011			✓
Bensmaine et al.	2011			✓
Bensmaine et al.	2011			✓
Bi	2011	✓		

Eguia et al.	2011				✓	
Gumasta et al.	2011	✓		✓		
Huang et al.	2011				✓	
Ma et al.	2011				✓	
Minhas et al.	2011					✓
Zhao	2011				✓	
Abdi	2012				✓	
Andrisano et al.	2012					✓
Azab and Gomoaa	2012				✓	
Bensmaine et al.	2012				✓	
Chaube et al.	2012			✓		
Goyal et al.	2012	✓			✓	
Guan et al.	2012				✓	
Gupta et al.	2012				✓	
Musharavati and Hamouda	2012				✓	
Musharavati and Hamouda	2012				✓	
Niroomand et al.	2012		✓			
Pellicciari et al.	2012		✓			✓
Saxena and Jain	2012				✓	
Wang and Koren	2012			✓		
Xie et al.	2012				✓	
Azab et al.	2013		✓			
Bensmaine et al.	2013				✓	
Bryan et al.	2013				✓	
Ferreira et al.	2013					✓
Garbie	2013		✓			
Goyal et al.	2013	✓				
Goyal et al.	2013				✓	
Hasan et al.	2013	✓				
Yu et al.	2013				✓	
Bensmaine et al.	2014				✓	

Borgo et al.	2014				✓	
Dammak et al.	2014					✓
Farid	2014	✓		✓		
Garbie	2014	✓				
Garbie	2014		✓			
Hasan et al.	2014	✓				
Maniraj et al.	2014				✓	
Mesa et al.	2014			✓		
Rabbani et al.	2014				✓	
Yingjie	2014		✓			
Azab and Naderi	2015				✓	
Choi and Xirouchakis	2015		✓		✓	
Elmasry et al.	2015			✓		
Gupta et al.	2015				✓	
Haddou-Benderbal et al.	2015	✓	✓		✓	
Hees and Reinhart	2015				✓	
Nayak et al.	2015					✓
Neto et al.	2015					✓
Aljuneidi and Bulgak	2016		✓			
Carpanzano et al.	2016				✓	
Dou et al.	2016				✓	
Eguia et al.	2016				✓	
Haddou-Benderbal et al.	2016		✓			
Koren et al.	2016			✓		
Scholz et al.	2016					✓
Unglert et al.	2016				✓	
Wang et al.	2016	✓		✓		
Wang et al.	2016				✓	
Azevedo et al.	2017				✓	
Bortolini et al.	2017					✓
Cohen et al.	2017					✓

Dubey et al.	2017	✓		
Haddou-Benderbal et al.	2017			✓
Hees et al.	2017			✓
Prasad and Jayswal	2017			✓
Saliba et al.	2017		✓	
Singh et al.	2017	✓		

3.2.3.1 Stream #1 – Reconfigurability level assessment

Metrics to measure the reconfigurability level of manufacturing systems allow providing quantitative data for RMS assessment. The availability of such metrics is milestoning to encourage the transition from traditional manufacturing systems to NGMSs and RMSs. However, a small number of studies make attempts to model the RMS characteristics and to develop a set of metrics to measure the reconfigurability level of a manufacturing system.

In this direction, the current research developed frameworks and models tackling the following aspects:

– Mapping the manufacturing system capabilities and characteristics providing a set of composite reconfigurability metrics defining indices for the main RMS attributes (Gumasta et al., 2011, Farid, 2014, Wang et al., 2016);
– RMS assessment through the definition of global reconfigurability indices (Goyal et al., 2012, Goyal et al., 2013, Hasan et al., 2013, Hasan et al., 2014, Haddou-Benderbal et al., 2015).

Gumasta et al. (2011) present an index to measure the reconfigurability of RMSs in terms of modularity, scalability, convertibility and diagnosibility. These characteristics are mapped together using multi-attribute utility theory. Farid (2014) provides a set of composite reconfigurability measures for integrability, convertibility and customisation, which have driven the qualitative and intuitive design of these technological advances. Wang et al. (2016) introduce quantitative models for the key characteristics of a RMS – scalability, convertibility, modularity, diagnosibility, integrability and customisation. Such models are, then, used as the basis to define a RMS evaluation index system by using the analytic hierarchy process (AHP) methodology to assign the weights for these indices.

Further relevant studies are in Goyal et al. (Goyal et al., 2012, Goyal et al., 2013) proposing three performance parameters (cost, operational capability and machine reconfigurability) for the selection of feasible machine configurations for RMSs. In addition, Hasan et al. (2014) propose an artificial neural network (ANN) model for a quantitative assessment of the reconfigurability level of RMSs.

In most cases, models and assessment methods include multi-criteria decision making (MCDM) techniques (Wang et al., 2009, Gumasta et al., 2011, Michalos et al., 2011, Goyal et al., 2012, Mourtzis et al., 2012, Goyal et al., 2013, Hasan et al., 2013, Farid, 2014, Garbie, 2014, Hasan et al., 2014, Wang et al., 2016). MCDM evaluates multiple conflicting criteria, supporting decision-makers in facing such problems. The main steps to apply a MCDM method include criteria selection, criteria weighting, evaluation and final aggregation (Huang and Kusiak, 1998). However, because of the choice of the weights to assign to each criterion is subjective, the results coming from the application of this methodology have not a general validity and depend on the specific application case.

Open challenges in the reconfigurability level assessment deal with mapping the production system attributes, out of the workstation boundaries, and the adoption of more rigorous analytic metrics. To this purpose, accurate and quantitative reconfigurability indices are still missing to take into account the effects of the material handling devices, the tools and fixtures in manufacturing environment even in the cases of multi-demand scenarios, multi-period planning horizon and multi-part manufacturing lines (Gumasta et al., 2011, Goyal et al., 2012).

3.2.3.2 Stream #2 – Analysis of RMS features

As mentioned in Section 3.2.1, modularity, integrability, diagnosibility, convertibility, customisation and scalability are the main features of RMSs (Setchi and Lagos, 2004, Bi et al., 2008, Koren and Shpitalni, 2010). In this section, the most relevant literature contributions examining these characteristics are analyzed.

3.2.3.2.1 Modularity

The modularity feature can be applied at both product and production system level. In the first case, modularity is the ability to design hardware and software components with modular attributes starting from standardised units and/or dimensions, generating flexibility and product variety enlargement (Chaube et al., 2012). In the latter case, modularity is the ability of the production system to use common units to create product variants (Gindy and Saad, 1998). In the field of RMSs, Yigit et al. (2002) and Yigit and Allahverdi (2003) propose a method for optimizing variety of modular products defining an optimal selection of the module instances. They propose a non-integer linear programming model to find acceptable trade-off between the potential quality loss due to modularity and the cost of reconfiguration. The model of Yigit et al. (2002) is suitable for two-module products, while Yigit and Allahverdi (2003) extend the model to make it suitable for products with any number of modules. Furthermore, Spicer et al. (2005) include modularity principles in the design of scalable reconfigurable equipment defining a mathematical approach to determine the optimal number of modules to include in a modular scalable machine. The Authors analyze the trade-off between the productivity advantages of additional modules and the productivity losses due to the resulting decreased availability. Mesa et al. (2014) define a design methodology to obtain RMSs integrating modular architectures, clustering algorithms and family product features to develop robust systems that allow easy reconfiguration and adaptation to new market requirements. Thanks to modularity, it is possible to obtain profitable systems that require only a partial reconfiguration and few additional fabrication modules for adapting to new products. Pattanaik et al. (2007) apply modularity principles to the design of machine cells for CMSs. For grouping modular reconfigurable machines capable of performing multiple operations, the Authors define a multi-objective evolutionary algorithm with two conflicting objectives based on some defined measures from several production parameters, machine–operation compatibility and alternative process plans.

3.2.3.2.2 Integrability

Integrability is the ability to include new systems and components within the existing production system, to integrate new technologies and to add or remove resources (Farid, 2014). In this field, Farid (2014) develops a reconfigurability measurement process to provide quantitative estimation of the integrability potential. In particular, the axiomatic design methodology is used to get production degree of freedom measures that represent the reconfiguration potential of a production system. To model the integrability metric each degree of freedom is discounted by the amount of effort required to integrate it into the rest of the system. In addition, Wang et al. (2016) model integrability as the ability to integrate components, e.g. manufacturing machines and control modules, through the component interfaces and the capability to integrate a new technique or process into the current system. In this study, the Authors prove the existence of an inverse relationship between software/hardware interface adjustment time and cost and the integrability of a RMS.

3.2.3.2.3 Diagnosibility

Diagnosibility is the ability of the system to self-check its current state detecting and diagnosing the causes of failures and product defects to correct and react accordingly (Gumasta et al., 2011). In this field, few research studies exist in literature. Bruccoleri et al. (2003) propose a distributed and intelligent control system to prove that the reconfiguration feature of machines is suitable for handling machine breakdowns. Three years later, Bruccoleri et al. (2006) add that out-of-ordinary events can be handled through reconfiguration, introducing the so-called *reconfiguration for error handling* concept and developing an object-oriented control architecture for error handling supported by reconfiguration.

3.2.3.2.4 Convertibility

Convertibility is the ability of the system to adjust production functionality or change from one product to another in response to the dynamic market changes. The literature proposes measures for the system convertibility considering configuration, machine and material handling convertibility in the same mathematical formulation, in which a weight is assigned to each of the three metrics (Maier-Speredelozzi et al., 2004, Singh et al., 2005, Gumasta et al., 2011). Farid (2014) considers convertibility metric as the sum of transformation and transportation convertibility. The former refers to the process plans, the latter to the material handling system. Wang et al. (2016) propose a mathematical formulation of the system convertibility as function of the ability of the system to produce different part families and different parts within the same family. These literature contributions try to include the convertibility measure in the development of a general reconfigurability index, in which all RMS characteristics are included and modelled (Gumasta et al., 2011, Farid, 2014, Wang et al., 2016).

3.2.3.2.5 Customisation

Customisation refers to the selection of machine tools and system components based on the flexibility need to processing a part family and specific parts. Farid (2014) and Wang et al. (2016) define a reconfigurability index that comprises a formulation for customisation metrics. In particular, Wang et al. (2016) model customisation according to product and functionality factors. The former refers to the design and selection of RMS configurations according to the part families, the latter refers to the need of a high utilisation rate of the equipment.

3.2.3.2.6 Scalability

Scalability is the ability to easily modify production capacity by adding or removing manufacturing resources (e.g. working machines) and changing components of the system in response to the changing demand. From a techno-economic point of view, this metric should be introduced in the design phase of a new RMS (Wang and Koren, 2012, Koren et al., 2016) and in the design of modular scalable machines (Spicer et al., 2005).

The scalability planning process requires to concurrently change system configuration and to rebalance the reconfigured system (Wang and Koren, 2012, Koren et al., 2016) in a cost-effective manner (Deif and ElMaraghy, 2007, Wang and Koren, 2012, Elmasry et al., 2015, Koren et al., 2016). The literature on the topic shows that the first study carried out in this field is by Son et al. (2001), defining a mathematical procedure for upgrading the capacity of serial lines composed of CNC machines. Wang and Koren (2012) propose a methodology for scalability planning in systems without buffers considering, as objective function, the minimization of the number of machines needed to meet the new market demand. In a more recent contribution, Koren et al. (2016) extend the previous study defining a mathematical model applied to systems with buffers in which the throughput after reconfiguration is maximized.

Deif and ElMaraghy (2006) define a capacity scalability dynamic model based on a control approach to indicate the best design for the scalability controller. In such a design, the Authors have to take trade-off decisions between system responsiveness and cost. Later on, Deif and ElMaraghy (2007) define a model for the capacity scalability planning in RMSs taking into account total investment costs. However, the model assumes that lead time is zero and rump-up is not considered. Gumasta et al. (2011) introduce a mathematical formulation of the scalability measure considering scalability as the ability to maintain cost effectiveness when workload grows. As in the case of convertibility metric, the scalability is included in the development of a general reconfigurability index (Gumasta et al., 2011, Wang et al., 2016).

3.2.3.3 Stream #3 – Analysis of RMS performances

Since 2002, an increasing number of researchers analyzes the performance of RMSs. In the following, discussion is from the strategic, i.e. high level, to the operational, i.e. daily activities, perspective.

3.2.3.3.1 Strategic perspective

The strategic perspective addresses decisions on the best allocation of investments among the portfolio of manufacturing systems in different product life cycle scenarios and according to the market and competitor behaviour. Several Authors propose models and techniques that allow considering strategic and long-term financial criteria in evaluating the suitability of DMSs, FMSs and RMSs to address the market expectations and fluctuations and to optimally allocating investments (Kuzgunkaya and ElMaraghy, 2007, Niroomand et al., 2012). As example, Kuzgunkaya and ElMaraghy (2007) define a fuzzy multi-objective mixed integer optimization model to evaluate RMS investments in a multiple product demand environment. The proposed model takes into account, as objective functions, the investment net present value (NPV), the average manufacturing system complexity and its responsiveness to meet high dynamic demand forecast. The Authors show that RMS outperforms FMS in terms of required investment level to match the production complexity. Their sensitivity analysis shows that shorter reconfiguration periods are needed to ensure the feasibility and profitability of RMS configurations. Niroomand et al. (2012) explore the best allocation of capacity investments among DMSs, FMSs and RMSs analysing the impact of the scalability and RMS ramp up behaviour on the optimal portfolio selection of manufacturing systems.

In particular, the Authors propose a mix integer programming model that maximizes the NPV. Results show that, if reconfiguration does not occur in a short time, RMS would behave similarly to DMSs and FMSs. Alexopoulos et al. (2007) introduce a method to assessing the flexibility of a manufacturing system under lifecycle considerations, providing an effective tool to support practitioners in manufacturing system investments. The flexibility is analyzed by statistical analysis of the discounted cash flow estimates of the manufacturing system lifecycle cost. Saliba et al. (2017) provide a set of structured guidelines, derived from the theory and from field studies, to evaluate the suitability of implementing RMSs in industry. Results indicate that many manufacturing companies recognise the benefits of RMSs but the potential of such systems may not yet be exploited to the full.

Additional analyzes including several model parameters as outsourcing levels, utilisation and machine module cost are of interest to provide decision makers with more insight about the available options (Kuzgunkaya and ElMaraghy, 2007).

3.2.3.3.2 Operational perspective

The operational perspective deals with the analysis of the main performances of RMSs according to three grouping categories, i.e. responsiveness (1), system complexity (2) and reliability and quality (3).

Responsiveness

The responsiveness of a manufacturing system is its ability to exploit available resources to quickly respond to uncertain market conditions (Matson and McFarlane, 1999, Singh et al., 2007) or as the ability to respond to internal or external factors impacting upon production goals (Kuzgunkaya and ElMaraghy, 2007, Manzini et al., 2009). The literature states that the introduction of RMSs should increase responsiveness level for surviving in uncertain market conditions (Abdi and Labib, 2003, Kuzgunkaya and ElMaraghy, 2007, Singh et al., 2007, Goyal et al., 2013, Haddou-Benderbal et al., 2015, Haddou-Benderbal et al., 2016). In particular, Goyal et al. (2013) and Haddou-Benderbal et al. (2015) model responsiveness in terms of operational capability and machine reconfigurability. Their results prove that with a marginal increase in the cost, RMSs, and in particular reconfigurable machine tools (RMTs), offer high responsiveness levels. Abdi and Labib (2003) and Singh et al. (2007) propose fuzzy AHP models to evaluate responsiveness, while Kuzgunkaya and ElMaraghy (2007) define a fuzzy multi-objective mixed integer optimization model to evaluate RMS investments taking lifecycle costs, responsiveness performance and system structural complexity as objective functions.

Future research opportunities in this area deal with the inclusion of multiple demand scenarios along with multi-part manufacturing lines. Furthermore, the effect of choosing higher values of machine responsiveness on the overall reconfiguration effort may be studied for multiple period planning horizon (Goyal et al., 2013).

System complexity

The dynamic market demand together with the rapid introduction of new technologies, products and materials increase the structural and dynamic complexity of manufacturing systems (Zhang et al., 2006, Kuzgunkaya and ElMaraghy, 2007, Singh et al., 2007). Singh et al. (2007) introduce a fuzzy AHP model to evaluate system complexity in a RMS environment. Kuzgunkaya and ElMaraghy (2007) define a fuzzy multi-objective model to evaluate RMS investments taking lifecycle costs, responsiveness performance and system structural complexity as objective functions.

Quality

Quality, among all the operational characteristics, is of great relevance. The literature on RMSs show that several Authors include quality issue:

- as criteria to design RMSs (Abdi and Labib, 2003), to select manufacturing system configuration and to justify the selection of a RMS (Maier-Speredelozzi and Hu, 2002, Singh et al., 2007);
- in the machine and product design, to evaluate RMTs in the equipment selection process (Abdi, 2009) and in the optimum selection of module instances for a modular product manufactured in a RMS (Yigit et al., 2002);
- as criteria for the selection of the most appropriate layout for each configuration stage, in addition to reconfigurability, cost and reliability (Abdi, 2005);
- as a milestone achieved by predicting and minimizing human errors in the early stages of manufacturing system configuration or reconfiguration (ElMaraghy et al., 2008).

Model and algorithms proposed in this field are generally solved adopting MCDM processes and, in particular, through AHP technique.

Availability and Reliability

The reliability of a system (or of a component of the system) over a given time is the probability that the system will not fail before the conclusion of that time, while the availability measures the probability of the system (or a component of the system) of working at a given instant of time (Elkington, 1997). Such issues have a great influence on RMS performances. Nonetheless, few studies exist in the literature. Youssef and ElMaraghy (2006) and Youssef and ElMaraghy (2007) define a model to optimize RMS configuration, minimizing the capital cost and maximizing the system availability of each configuration. In the same field, Haddou-Benderbal et al. (2015) and Haddou-Benderbal et al. (2016) analyze the impact of machine unavailability on the efficiency of the RMS, finding the best alternative solution to ensure the system responsiveness in the case of machine unavailability. Kuruvilla et al. (2008) introduce an approach to evaluate the reliability of reconfigurable conveyor systems, providing insights into the structural, operational and monitoring reliability of these systems. The small number of contributions identified in the literature confirms the need to carry on research activities in this field to identify the main causes and modelling techniques for unavailability and unreliability of RMSs.

3.2.3.3.3 Sustainability perspective

The literature models the sustainability issue according to the Triple Bottom Line (TBL) concept. This concept is introduced by Elkington [146] that marks the distinction among the environmental, economic and social dimensions of sustainability [146-148]. The inclusion of the sustainability issues is a key aspect for an efficient design and management of RMSs (Bi, 2011, Pellicciari et al., 2012, Azab et al., 2013, Garbie, 2013, Gabrie, 2014, Yingjie, 2014, Choi and Xirouchakis, 2015, Michalos et al., 2015, Aljuneidi and Bulgak, 2016, Dubey et al., 2017). Despite the first definition of RMS appears in 1999, the literature review shows that the investigation of a possible relationship between RMS and Sustainable Manufacturing (SM) is fairly recent. Despite several Authors focus on the environmental dimension and others on the economical dimension of sustainability applied to RMSs, few studies propose models and techniques to assess the social dimension of sustainability, especially from a quantitative perspective, as in Table 8.

Table 8: Classification of papers about sustainability of RMSs

Authors	Year	Sustainability		
		Environmental	Economical	Social
Bi	2011	✓		

Pellicciari et al.	2012	✓		
Azab et al.	2013	✓	✓	✓
Garbie	2013		✓	
Garbie	2014	✓	✓	✓
Yingjie	2014	✓	✓	
Choi and Xirouchakis	2015	✓	✓	
Aljuneidi and Bulgak	2016	✓		
Dubey et al.	2017	✓		

The most of the published papers on the environmental dimension analyzes general environmental concepts without any link to the economic and/or social dimensions. According to Garbie (2013) and Dubey et al. (2017) higher reconfigurability of manufacturing systems leads to better environmental and economic performance as well as to reduce the energy consumption.

3.2.3.4 Stream #4 – Applied research and field applications

This section presents the main fields of application of RMSs proposed by the literature. The main areas covered by this research stream are inbound Reconfigurable Transportation Systems (RTSs), the layout problem, the product-family formation problem, the development of reconfigurable cellular manufacturing systems, the RMS configuration selection and the scheduling problem in RMSs.

3.2.3.4.1 Inbound Reconfigurable Transportation Systems (RTSs)

Inbound transportation systems are one of the major application area of the reconfigurability concepts, designed as multiple independent modules for the implementation of alternative inbound logistic system configurations (To and Ho, 2002, Borgo et al., 2014, Carpanzano et al., 2016). Carpanzano et al. (2016) propose an innovative agent-based algorithm to manage the part flow in RTSs. The proposed model allows routing decisions while embracing global and local evolving optimization strategies. Kuruvilla et al. (2008) define a model-based approach to evaluate the reliability of composable conveyor systems equipped with networked embedded devices. Their study shows that while using redundant sensors has little effect on system-level reliability, wireless link reliability has a significant impact. Except for these few contributions, the literature review shows that the most of the research investigates and applies the reconfigurability principles at the machine level, only. Studies focusing on the application of such principles at the inbound transport system level are rare and expected.

3.2.3.4.2 Layout problem

RMSs are designed to perform different operations on various products grouped in families according to their operational requirements. The layout design and optimization is a key issue in the field of RMSs (Wu et al., 2007) since these systems require different layout configurations switching by one product family to another (Yamada et al., 2003). In the literature, the Authors investigate the layout design, management and optimization defining optimal and heuristic models. Yamada et al. (2003) propose a model for the layout optimization of manufacturing cells and an allocation optimization method for transport robots by using particle swarm optimization (PSO) algorithm. Abdi (2005) explores the criteria that may influence the choice of the layout configuration for each configuration stage and defines an AHP model to structure the proposed criteria (reconfigurability, quality, cost and reliability) for the selection of the most appropriate layout. Guan et al. (2012) and Azevedo et al. (2017) face the layout design problem defining single and multi-objective optimization models. In particular, Guan et al. (2012) define a revised electromagnetism-like mechanism (REM) for the layout design of RMSs using automated guided vehicles (AGVs) as transportation systems and considering, as single-objective function, the minimization of the material handling costs. The proposed model produces optimal solutions just for small-scale problems. Azevedo et al. (2017) make a first attempt to overcome the main limits existing in the literature as the consideration of a single objective in the definition of models addressing the layout design problem. They introduce a multi-objective approach addressing the reconfigurable multi-facility layout problem considering as objective functions the minimization of material handling costs, the maximization of the adjacency among departments and, finally, the minimization of the unsuitability of the department position and location. Further research opportunities deal with the introduction of multi-objective meta-heuristic techniques to efficiently solve larger real size instances and the integration of simulation models with optimization techniques to face the uncertain aspects of the problem. The adoption of optimization combined to simulation is widespread in the literature since the output of the simulation is used by the optimization module to provide feedbacks on the progresses of the search for an optimal solution (Bensmaine et al., 2011).

3.2.3.4.3 Product family formation for RMSs

In a typical RMS, products are grouped in families and each of them requires a different system configuration. In this way, the system is configured to produce the first family and, once the production is finished, the system is reconfigured to produce the second family and so on (Xiaobo et al., 2000; Xiaobo et al., 2000, Xiaobo et al., 2001, Xiaobo et al., 2001, Galan et al., 2007, Galan, 2008, Zhang and Qiu, 2008, Rakesh et al., 2010, Gupta et al., 2012, Pellicciari et al., 2012, Bryan et al., 2013, Goyal et al., 2013). Approaches and methods for grouping products into families and for assigning the best family to each reconfiguration stage are necessary.

In the field of RMSs, product families are based on operational similarities among parts (Abdi and Labib, 2004, Galan et al., 2007, Rakesh et al., 2010, Abdi, 2012) or on operation sequence similarity (Gupta et al., 2012, Goyal et al., 2013). However, few grouping methods are proposed and tested for RMSs, e.g. clustering techniques and MCDM methods as AHP (Abdi and Labib, 2004, Galan et al., 2007, Zhang and Qiu, 2008, Ma et al., 2011) and Analytical Network Process (ANP) (Abdi, 2012). Table 9 shows a match of recent papers to the adopted family formation technique.

Table 9: Classification of methods used in the product family formation in RMS environment

Authors	Year	Clustering techniques	MCDM
Abdi and Labib	2004	✓	✓
Galan et al.	2007	✓	✓
Zhang and Qiu	2008	✓	✓
Rakesh et al.	2010	✓	
Ma et al.	2011	✓	✓
Abdi	2012		✓
Gupta et al.	2012	✓	
Goyal et al.	2013	✓	
Wang et al.	2016	✓	

Abdi and Labib (2004) introduce an approach for grouping products into families based on operational similarities through a modified *Jaccard* similarity index. Once product families are defined, the Authors propose an AHP model to find the most suitable family for each reconfiguration stage. Galan et al. (2007) and Zhang and Qiu (2008) propose a methodology for the formation of product families in a RMS environment, based on five key product characteristics, i.e. modularity, commonality, compatibility, reusability and product demand. The AHP methodology is applied to weight these attributes according to their importance and to aggregate them in a single coefficient. Gupta et al. (2012) define a three-stage part family formation method based on operation sequence similarity. This method builds a similarity coefficient matrix for parts. Then, the part families are defined after identifying the parts with the closest correlation. Finally, the results of the previous steps are optimized using an agglomerative hierarchical clustering algorithm. Goyal et al. (2013) and Wang et al. (2016) define a method for part family formation in a RMS environment considering bypassing movements and idle machines. Goyal et al. (2013) use ALC to cluster products and propose a similarity coefficient based on operation sequence. Such a methodology evaluates the differences among parts by measuring the number of idle machines and bypass movements considering fix operation sequences for the products. Rakesh et al. (2010) overcome this limit considering that each part can be manufactured with alternative operation sequences. Wang et al. (2016) propose a new formation method for RMS. The proposed methodology considers both bypassing movements and idle machines with the goal of minimizing idle machines and improving the smoothness of the part movements. Compared to the algorithms developed in this field, the proposed method shows higher computational efficiency and improves the accuracy of the part-family formation process.

The most of the above studies about the formation of part families does not take into account important production factors, as the processing times and the production volumes, key elements for improving the efficacy and the accuracy of the part-family formation process. Efforts in this direction are expected.

3.2.3.4.4 Reconfigurable Cellular Manufacturing Systems

The current dynamic production environment leads to the formation of dynamic cellular manufacturing systems in which cells are reconfigured within multiple planning periods (Bai et al., 2009, Rabbani et al., 2014, Eguia et al., 2016). In a standard Cellular Reconfigurable Manufacturing System (CRMS), cells have modular machines, composed by basic and auxiliary modules, able to perform different tasks and operations (Pattanaik et al., 2007, Eguia et al., 2016, Unglert et al., 2016). In this field, the literature proposes mathematical models to address the design and management of RCMSs. Table 10 provides a review of them.

Table 10: Classification of mathematical methods for the CRMS problem

Authors	Year	Method	Objective functions
Pattanaik et al.	2007	Multi-objective optimization	Minimize inter-cell part movements Minimize total changes in auxiliary modules Maximize sum of conjoint product similarity coefficient
Bai et al.	2009	Multi-objective optimization	Minimize reconfiguration costs Minimize machine loading unbalance Minimize working overtime Minimize inter-cell part movements
Rabbani et al.	2014	Multi-objective optimization	Minimize sum of miscellaneous costs Maximize utilisation rate of machines
Eguia et al.	2016	Single-objective optimization	Minimize inter-cell movements and voids (design phase) Minimize transportation and holding costs (management phase)

The literature shows that the most of the existing contributions explore such an issue from a multi-objective perspective, adopting both linear and non-linear formulations. Eguia et al. (2016) explore the RCMS problem in presence of alternative routings and multiple periods to design RCMSs and, then, to load the cells.

Pattanaik et al. (2007) propose a methodology to identify working cells using a multi-objective evolutionary GA, while Bai et al. (2009) define an approach for the formation of virtual manufacturing cells in a RMS environment with multiple product orders. Rabbani et al. (2014) explore the idea of machine modification through a mixed integer non-linear mathematical model. The Authors develop an Imperialist Competitive Algorithm (ICA) and, then, compare the obtained results with those of a GA. Finally, Unglert et al. (2016) outline the adoption of Computational

Design Synthesis (CDS) to support decision making by automating the generation of solution proposals to the design problem. Furthermore, such a methodology allows analysing design candidates to compare them in terms of performance. In this field, further research opportunities deal with the inclusion of random machine failures and disturbances to test the robustness of the solutions as well as the consideration of set-up in the production setting (Eguia et al., 2016).

3.2.3.4.5 RMS configuration selection

The selection of the best RMS configuration is among the most important choices in the management of a RMS (Youssef and ElMaraghy, 2007, Dou et al., 2010, Koren and Shpitalni, 2010, Huang et al., 2011). It includes the set of decisions that significantly impact on performances as the arrangement of the machines, the equipment selection and the operation assignment (Youssef and ElMaraghy, 2006, Youssef and ElMaraghy, 2007, Youssef and ElMaraghy, 2008). In this field, researchers propose methodologies for best managing such an issue, e.g. optimization models, meta-heuristic, MCDM models.

In the field of optimization, a clear distinction is between the use of single or multi-objective optimization models. The literature analysis shows that cost is the most widely analyzed key performance indicator (KPI) [44, 54, 58, 64, 72, 88] while GA is the most widely used meta-heuristic (Youssef and ElMaraghy, 2006, Youssef and ElMaraghy, 2007, Youssef and ElMaraghy, 2008, Dou et al., 2010) for the selection of the best RMS configuration. Youssef and ElMaraghy (2006) propose a model for optimizing the capital cost of RMS configuration using GA. The model produces a set of different alternatives so that the designer can choose the best one in the design phase or at the beginning of each configuration period. This work neglects the machine downtime, while Youssef and ElMaraghy (2007) and Youssef and Elmaraghy (2008) upgrade the study introducing GAs and Tabu Search (TS) approaches for the continuous optimization of capital flow and system availability. Dou et al. (2010) propose a GA-based approach for the optimization of the capital cost of multi-part flow-line (MPFL) configurations of a RMS for a part family. In this study, the Authors compare the obtained results with those obtained applying a PSO algorithm to prove the effectiveness of the proposed approach. Saxena and Jain (2012) define a configuration design methodology for RMSs aiming at the optimization of an economic objective function including capital cost of machine investment, reconfiguration cost, operating cost, maintenance cost and residual marginal value over time. The proposed model is solved using Artificial Immune System (AIS). Huang et al. (2011) use a modified Simulated Annealing (SA) for managing the configuration selection problem in RMSs optimizing an economic objective function that includes the reconfiguration cost and the fixed cost in the given reconfiguration period. Finally, Xiaobo et al. (2000) propose a stochastic model optimizing the average expected profit over an infinite horizon to find the best configuration alternative for the production of each family within a RMS environment.

In parallel, a wide number of researchers explores the problem of the selection of candidate reconfigurable machines using multi-objective methods. The literature review shows that the cost and the total completion time are the most widely analyzed KPIs and that GA is the most widely meta-heuristic used for addressing such an issue (Goyal et al., 2012, Xie et al., 2012, Bensmaine et al., 2013, Haddou-Benderbal et al., 2015, Dou et al., 2016). Goyal et al. (2012) introduce a multi-objective model for the optimal machine assignment for a single part flow line. The proposed model aims at investigating the trade-off between the economy and the responsiveness of the RMS minimizing the cost of feasible alternative machine configuration and maximizing the operational capability and the machine reconfigurability. Bensmaine et al. (2013) and Haddou-Benderbal et al. (2015) introduce an approach for the RMS design problem and the selection of machine configuration optimizing the total cost and the total completion time, in the former study, and the total completion time and the perturbation caused by the unavailability of selected machines in the latter.

Xie et al. (2012) integrate the production process design with the configuration problem of RMTs proposing a cooperative optimization method of such issues to improve product quality and reduce production costs. Dou et al. (2016) integrate configuration generation problem and scheduling for reconfigurable flow lines and define a bi-objective model optimizing the capital and the reconfiguration cost as well as the total tardiness.

As discussed previously, MCDM is used for the evaluation of the best configuration with respect to a set of performance criteria that allow the rank of the alternative configurations (Maier-Speredelozzi and Hu, 2002, Dou et al., 2007, Rehman and Subash Babu, 2009, Gupta et al., 2015).

3.2.3.4.6 Planning & Scheduling in RMSs

The scheduling problem includes a set of decisions about the sequence of parts to be released into the systems, the selection of the operation/machine pair and the sequence of parts assigned to each machine (Aiping and Nan, 2006, Yu et al., 2013). In this field, optimization models addressing such an issue are proposed. Yu et al. (2013) and Azab and Naderi (2015) define mathematical models in which the make-span is minimized. The proposed models are solved using SA and GA heuristics. Galan (2008) introduces a multi-objective model to optimize the production scheduling in which the costs required to reconfigure the system are minimized and the capacity and functionality of the machines are maximized. In addition, Dou et al. (2016) integrate configuration generation problem and scheduling for reconfigurable flow lines and define a bi-objective model optimizing the capital and the reconfiguration cost and the total tardiness. Bensmaine et al. (2014) tackle the integrated process planning and scheduling (IPPS) problem defining a GA procedure that takes into account the multi-configuration nature of RMSs. Prasad and Jayswal (2017) propose a reconfigurable layout for an assembly line and perform a scheduling of the products taking into account reconfiguration effort, profit over cost and due date. In particular, scheduling has been done using the integrated approach of Shannon Entropy and Reference Ideal Method.

Production planning in RMSs

Abbasi and Houshmand (2009) and Abbasi and Houshmand (2011) address the production planning problem in RMS environment introducing mixed-integer non-linear programming (MINLP) models for optimizing the total profit, in which a stochastic product demand is supposed. The proposed models aim to determine the optimal sequence of production tasks and the corresponding configurations and batch sizes. Meta-heuristics as TS and GA are used to solve the proposed models (Fan and Tan, 2002, Azab and Gomoaa, 2012, Xie et al., 2012). Xie et al. (2012) integrate the production process plan design with the configuration of RMTs proposing a cooperative optimization of such issues to improve product quality and reduce production costs. Azab and Gomoaa (2012) tackle the operation sequencing problem and define an integer based model in which the changeover time among successive sub-operations is minimized. Hees and Reinhart (2015) and Hees et al. (2017) propose new approaches for production planning in RMSs able to integrate RMS's main characteristics in production planning and control. Other relevant studies that propose models for addressing the production planning problem are in Dammak et al. (2014) and Choi and Xirouchakis (2015).

Process plan generation in RMSs

Musharavati and Hamouda (2012) and Musharavati and Hamouda (2012) tackle the problem of optimizing process planning in a RMS environment using SA algorithms. The objective is to minimize the overall manufacturing cost, e.g. process change cost, set-up change cost, tool change coss, reconfiguration change cost, etc.. Bensmaine et al. (2011), Bensmaine et al. (2011) and Bensmaine et al. (2012) address the problem of process plan generation in RMSs considering their multi-configuration nature. The Authors propose multi-objective models for the continuous optimization of the completion time, the total cost and the reconfiguration effort by using meta-heuristics as simulation-based NSGA-II and Archived Multi-Objective Simulated Annealing (AMOSA). In these studies, simulation technique plays a relevant role since it is used for performance evaluation and, iteratively, the output of the simulation is used by the optimization module to provide feedback on the progress of the search for an optimal solution. Maniraj et al. (2014) define optimal process plans for a single-product flow-line RMS using an Ant Colony Optimization (ACO) approach in which a total cost function is minimized. Haddou-Benderbal et al. (2017) introduce a study to addressing the problem of machine selection for RMS design. The Authors develop an approach based on NSGA-II to ensure the best process plan according to the customized flexibility required to produce all products. Two objectives are considered in the analysis, respectively, the maximization of the flexibility index of the system and the minimization of the total completion time.

In this field, the literature analysis shows that the cost is the most widely analyzed KPI and that the use of meta-heuristic methodologies addressing such issues is widely spread.

3.2.3.5 Stream #5 – Reconfigurability toward Industry 4.0

The term *Industry 4.0* derives from a project in the high-tech strategy of the German government in 2011 for promoting the computerisation of manufacturing (Saldivar et al., 2015) and, in the last few years, the *Industry 4.0* emerged as the fourth industrial revolution (Dregger et al., 2016). In this new era, digital manufacturing plays a crucial role (Rubmann et al., 2015) and digital manufacturing technologies are keys enabling technologies for future manufacturing (Scholz et al., 2016). In particular, the nine key enabling technologies characterising the upcoming industrial revolution, supporting its implementation in the industrial context, are in Figure 18 (www.sviluppoeconomico.gov.it, Garza-Reyes, 2015).

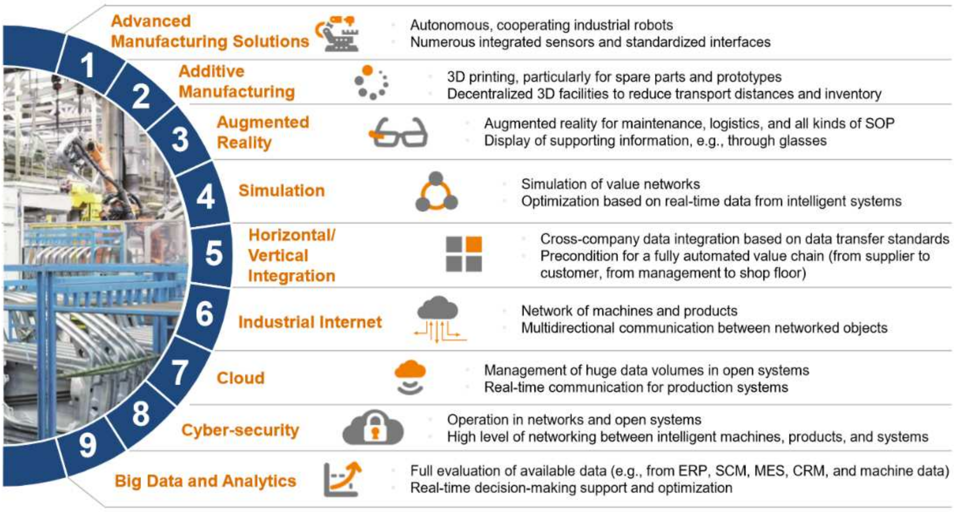

Figure 18: Industry 4.0 enabling technologies (www.sviluppoeconomico.gov.it, Garza-Reyes (2015))

Among these technologies, the first one, i.e. Advanced Manufacturing Solutions, plays a crucial role and refers to the set of autonomous, cooperating industrial robots and to the class of modular manufacturing systems characterised by integrated sensors and standardised interfaces. Modular RMSs, changeable and smart manufacturing and assembly systems fall within this category. This means that they are part of the *Industry 4.0* environment and contribute to the development of the factories of the future, called smart factories. Such factories adapt themselves to the dynamic environment and they use RMSs because they are rapidly reconfigurable (Nayak et al., 2015). In such an environment, a small number of Authors starts to explore the idea of integrating reconfigurability together with the other *Industry 4.0* technologies in the design and management of advanced production systems (Pellicciari et al., 2012, Ferreira et al., 2013, Nayak et al., 2015, Neto et al., 2015, Scholz et al., 2016). Manufacturing systems are equipped with sensors, actuators and control architectures for achieving agility and elasticity (Minhas et al., 2011, Ferreira et al., 2013) and for enabling the integration of real time data sources into service oriented architectures (Neto et al., 2015). Pellicciari et al. (2012) and Andrisano et al. (2012) state that reconfigurability and hybridisation are the main drivers for changeability and introduce the concept of Hybrid Reconfigurable Systems (H-RSs) as systems characterised by both industrial robots and skilled human workers, able to perform complex tasks within a common reconfigurable production environment. The studies in Bortolini et al. (2017) and Cohen et al. (2017) describe the impact of *Industry 4.0* principles on manufacturing and assembly system design. Bortolini et al. (2017) analyze the industrial environment evolution over the last three centuries highlighting the technology innovations which enabled the manufacturing process digitalisation, while Cohen et al. (2017) provide a general architecture to implement reconfigurability and *Industry 4.0* technologies in existing manufacturing and assembly systems and in the design of new smart systems though a case study of an Italian industrial refrigerator manufacturer.

Among the five research streams reported in the schematic map of Figure 4, such stream is still the less explored because of the novelty of the *Industry 4.0* environment. Nevertheless, several institutions and research centres show an increasing interest toward this topic as demonstrated by the proposal of several funding projects, e.g. *Horizon 2020* programme, and by a gradual increase in the number of research publications.

3.2.4 Summary and final remarks

Nowadays, industrial companies face a wide number of challenges since customers ask for a high variety of customized high-quality products in flexible batches with a dynamic market demand. To overcome the limitations of the traditional manufacturing systems, the Next Generation Manufacturing Systems (NGMSs) provide an increased level of flexibility, reconfigurability and intelligence. Reconfigurable Manufacturing Systems (RMSs) are within NGMSs and seem to have the potential to meet the current production trends. This paper presents a systematic review of the most relevant existing literature on RMSs to provide researchers and practitioners with an overview on the topic. 129 articles, peer-reviewed papers, book chapters and indexed international conference papers published between 1999 and 2017 are included in the review. A schematic map identifying five research streams in the field of RMS is proposed together with the main open issues. The literature analysis shows that some research streams have received good attention from the research community, e.g. analysis of RMS features (Stream #2), analysis of RMS performances (Stream #3) and applied research and field applications (Stream #4), while others still require further research, e.g. reconfigurability level assessment (Stream #1) and reconfigurability toward *Industry 4.0* (Stream #5). The major findings of this study are (1) the need for the adoption of more rigorous analytic metrics to assessing reconfigurability level since accurate and quantitative RMS reconfigurability indices are still missing and (2) the need for successful case studies and best practices efficiently driving the transition of modern industrial companies toward reconfigurable manufacturing.

According to such results, Table 11 provides future research paths, highlighting crucial open research questions for the future development of the RMSs within academia and modern industry. The formulation of open research questions is the most effective strategy to highlight and guide future research.

Table 11: Open issues to guide further research

Open issues
1. In the current production environment, do industrial companies have a clear view of the emerging market trends and of the need of adopting these emerging production systems?
2. Is it possible to make reconfigurable a production system not designed to be? Is it necessary to include reconfigurability principles just in the design phase of such systems?
3. From an economic point of view, is it possible to introduce reconfigurability principles in an existing production system without making any new substantial investments?
4. What are the characteristics of an effective assessment method or indicator for a RMS?
5. When assessing the reconfigurability index of a production system using methods and indicators proposed by the current literature, have the obtained value be evaluated with respect to what?
6. Is there a need to develop more objective-based reconfigurability index, able to overcome the use of MCDM and subjective methodologies?
7. Can the current RMSs measurement methods, indicators and models already proposed in the literature for the proposed five research streams be applicable or adapted to different processes or industries?

Answering to these questions is a first starting point to expand the knowledge on RMSs and to support industry and practitioners in the transition toward the introduction of reconfigurable manufacturing. Furthermore, similar and/or additional research questions can be formulated to expand the RMS research in other underreported areas, issues and industries.

Next Section 3.3 fills one of the identified research gap, defining an original mathematical optimization model supporting the design and management of Cellular Reconfigurable Manufacturing Systems (CRMSs), rising as emerging systems matching the current industrial and market requirements and able to overcome some weakness of conventional CMSs.

3.3 RECONFIGURABILITY IN CELLULAR MANUFACTURING SYSTEMS: A DESIGN MODEL AND MULTI-SCENARIO ANALYSIS

In conventional Cellular Manufacturing Systems (CMSs) similar parts or products are grouped to create families, while the required working machines compose manufacturing cells with the aim of reducing production time, setups, work-in-process, increasing quality and the system productivity (Singh, 1993, Wemmerlov and Johnson, 1997, Defersha and Chen, 2005). This production philosophy integrates the benefits of flexible and mass production systems cutting down the system operation costs (Sarker, 2001, Chan et al., 2008). Experiences of Cellular Manufacturing (CM) implementation in industry and performance improvements are studied widely by the scientific literature (Wemmerlov and Johnson, 1997, Pattanaik and Sharma, 2009, Bortolini et al., 2011). Particularly, several approaches are discussed by researchers in the last decades to increase the performances of CM systems. Optimal, heuristic and meta-heuristic procedures are used. As example, Ateme-Nguema and Dao (2007) proposed a hybrid approach to solve the cellular systems design problem for large industrial data sets introducing an ant colony optimization and tabu search procedure. The goal is to minimize the dissimilarities among machines or parts. Luo and Tang (2009) presented a model combining ordinal optimization and iterated local search to maximize the grouping efficacy index. Ghezavati and Saidi-Mehrabad (2010) introduced a mathematical model for the cell formation problem integrated with group scheduling decisions with the aim of minimizing the total costs.
In the last few years, an increasing number of factors such as short lead times, dynamic market demand, fluctuating volumes and high customized variants drive the transition from traditional manufacturing systems toward the so-called Next Generation Manufacturing Systems (NGMSs) (Mehrabi et al., 2000, Mehrabi et al., 2002, Molina et al., 2005, Hasan et al., 2014). In this context, traditional systems as Dedicated Manufacturing Systems (DMSs), Flexible Manufacturing Systems (FMSs) and CMSs show increasing limits in adapting themselves to the recent industrial and market trends (Bortolini et al., 2018). Focusing on CMSs, once machine cells are designed, the physical

relocation of the facilities included in each cell in response to new production requirements becomes difficult. To overcome such and other weaknesses, the recent research focuses on modularity to designing manufacturing cells using modular machines achieving reconfigurability in manufacturing (Pattanaik et al., 2007, Eguia et al., 2017). According to the original definition, a Reconfigurable Manufacturing System (RMS) is *'designed at the outset for rapid change in structure as well as in hardware and software components to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements'* (Koren et al., 1999, Koren, 2006). Such systems include the so-called Reconfigurable Machine Tools (RMTs) characterized by an adjustable and modular structure that enables machine scalability and convertibility using basic and auxiliary manufacturing modules (Landers et al., 2001, Asghar et al., 2018, Moghaddam et al., 2018) increasing the set of the feasible operations (Eguia et al., 2017). Typically, basic modules are structural in nature, while auxiliary modules are kinematical or motion-giving. A combination of these modules provides the operational capability to the RMT. In the recent years, numerous attempts are made to merge CMSs and RMSs to overcome the main shortcomings of cellular manufacturing. The concept of Cellular Reconfigurable Manufacturing System (CRMS) is introduced. CRMSs are made of a set of Reconfigurable Machine Cells (RMCs) in which machines are logically, instead of physically, organized (Xing et al., 2009). This means that RMCs can change during the production plan horizon by changing the auxiliary custom modules on the RMTs. In this field, methods and models for the cell formation problem using reconfigurable machines are in Pattanaik et al. (2007) and Pattanaik and Kumar (2010). The Authors proposed a clustering-based approach supporting the design of RMCs using modular machines. Xing et al. (2009) introduced an approach to design and control CRMSs by using artificial intelligence, focusing on the formation of RMCs coming from the dynamic and logical clustering of subsets of manufacturing resources. Bai et al. (2009) introduced an approach for the formation of virtual manufacturing cells in a reconfigurable manufacturing environment characterized by multiple product orders. Javadian et al. (2011) presented a multi-objective dynamic cell formation model, minimizing the total cell load variation and the sum of the miscellaneous costs. Rabbani et al. (2014) addressed the reconfigurable dynamic cell formation problem proposing a mixed integer non-linear mathematical model. Since such formulation is NP-hard, the Authors developed an Imperialist Competitive Algorithm (ICA) and compared the results respect to a genetic algorithm. Unglert et al. (2016) presented a design model of CRMSs that allows the automatic design and analysis of different system configurations. This approach enables the decision makers to evaluate different system performances of various system configurations. Eguia et al. (2013) solved the cell formation problem and the scheduling of part families for CRMSs defining a mixed integer linear programming model minimizing the production costs. Yu et al. [33] defined an optimization model to integrate part grouping and loading in such systems, minimizing the workload assigned to the machines. Eguia et al. (2017) extended the previous formulation by considering multiple process plans for each part and RMT with a library of auxiliary modules and introduced a mathematical model that minimizes the transportation and holding costs. Aljuneidi and Bulgak (2016) presented a mathematical model for the joint investigation of CRMSs and hybrid manufacturing-remanufacturing systems. Such model considers a conventional cell formation problem in CMSs bridged with a production planning problem addressing the 'reconfiguration' issues of CMSs for different production periods.

Starting from this scenario, this paper presents an original procedure, based on a linear programming model, to optimally design and manage CRMSs from a multi-product and multi-period perspective, exploring how to best-balance the part flows and the effort to install the modules on the machine on which the part is located. To the Authors' knowledge, the trade-off analysis between inbound logistics and machine reconfiguration is new and it has never been explored by the literature. The proposed model minimizes the inter-cell parts travel time and the setup time to assemble and disassemble the auxiliary modules. In addition, a multi-scenario analysis studies the effect of different machine-cell configurations on these system performances.

According to the introduced background and the outlined goals, the reminder of this Section is organized as follows: Section 3.3.1 states the problem and describes the linear programming model supporting the design and management of CRMSs, while Section 3.3.2 applies the model to a representative case study frequently adopted in the CM literature to benchmark the proposed algorithms. The multi-scenario analysis is in Section 3.3.3 before concluding the study in the last Section 3.3.4.

3.3.1 Problem statement and analytic modelling

CRMSs include multiple RMCs made of a set of machines, i.e. RMTs. Each RMT has a library of basic and auxiliary customized modules. The basic modules are structural elements permanently attached to the RMT while auxiliary modules are kinematical or motion-giving, e.g. spindles, and they can be assembled or disassembled to provide different operational capabilities. In this paper, according to recent literature (Pattanaik et al., 2007, Eguia et al., 2017), the reconfigurability attribute is modeled in terms of modularity of the existing RMTs. Figure 19 shows a schematic framework of the considered CRMS structure.

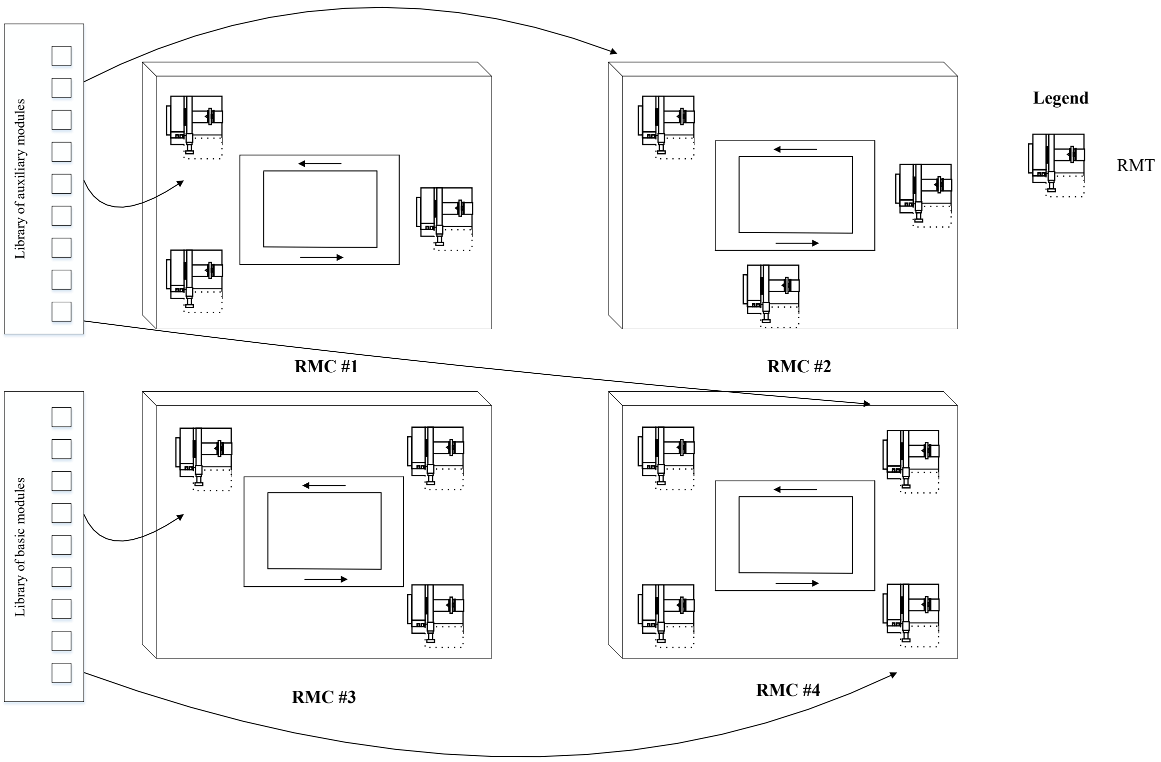

Figure 19: Schematic framework of a CRMS structure

3.3.1.1 Problem descriptions, assumptions and notations

The proposed CRMS design procedure starts from a given RMT-RMC assignment and, by using the information about the operation sequence and the compatibility among auxiliary modules, operations and RMTs, explores how to best-balance the part flows among RMCs and the effort to install the auxiliary modules on the RMT on which the part is located. To address this issue, the proposed optimization model minimizes the inter-cell parts travel time plus the setup time to assemble and disassemble the auxiliary modules, determining the product batch flows and the best allocation of the modules to the RMTs.

In the model development, the following assumptions are adopted, following the standard literature (Pattanaik et al., 2007, Eguia et al., 2017):

- the operation-based process plan for the parts is given;

- the requirement of modules and the RMT-module compatibilities are given;
- the auxiliary modules are available when needed;
- the reference RMT-RMC assignment is given, i.e. initial RMT-RMC layout. This condition is realistic because the existing industries have a defined layout and re-layout actions are time and cost consuming and may be assessed starting from the outcomes of the proposed model;
- working and setup times, e.g. auxiliary modules assembly and disassembly times, together with part travel times are known and deterministic.

The following notations are introduced.

- Indices

i	parts $i = 1, \dots, M$
o	operations of the part work cycle $o = 1, \dots, O_i$
m	RMTs $m = 1, \dots, Z$
k	auxiliary module types $k = 1, \dots, L$
j	RMCs $j = 1, \dots, N$
t	time periods $t = 1, \dots, T$

- Parameters

G_{omk}	1 if operation o can be performed on RMT m using auxiliary module type k; 0 otherwise $[binary]$
r_{it}	definition of the operation in which the batch of part i is in period t
t_{ijj_1}	travel time for batch of part i from cell j to cell j_1 $[min/batch]$
λ_{mk}	assembly time of module k on RMT m $[min/module]$
μ_{mk}	disassembly time of module k from RMT m $[min/module]$
τ_{om}	time to perform operation o on RMT m $[min/op]$
MAC_{mj}	1 if RMT m is assigned to cell j; 0 otherwise $[binary]$
ξ	available time per RMT and time period $[min/machine]$
R	maximum number of modules per RMT and period [#]
δ_i	planned production volume per period of time for part i [*parts*]

- Decisional variables

F_{ijj_1t}	1 if batch of part i moves from cell j to cell in j_1 in period t; 0 otherwise $[binary]$
W_{mit}	1 if batch of part i is processed by RMT m in period t; 0 otherwise $[binary]$
σ_{mkt}	1 if module k is on RMT m in period t, 0 otherwise $[binary]$
X_{mkt}	1 if module k is assembled on RMT m in period t, 0 otherwise $[binary]$
Y_{mkt}	1 if module k is disassembled from RMT m in period t, 0 otherwise $[binary]$

- Objective function

ψ Total part travel time and module assembly/disassembly time $[min]$

The analytic formulation of the proposed CRMS design model is in the following.

$$\min \psi = \sum_{m=1}^{Z}\sum_{k=1}^{L}\sum_{t=1}^{W} X_{mkt}\cdot\lambda_{mk} + \sum_{m=1}^{Z}\sum_{k=1}^{L}\sum_{t=1}^{W} Y_{mkt}\cdot\mu_{mk} + \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{t=1}^{W-1} F_{ijj_1t}\cdot t_{ijj_1} \quad (1)$$

(1) minimizes the sum of three relevant terms having opposite trends. i.e. the time to install the auxiliary modules on the RMTs, the time to disassemble the modules from the RMTs and the inter-cell part travel time. The model is subject to the following feasibility constraints:

$$\sum_{m=1}^{Z} W_{mit} = 1 \qquad \forall t, i \quad (2)$$

$$G_{omk}\cdot W_{mit} \le \sigma_{mkt} \qquad \forall\, m, i, k, t, o\colon r_{it} = o \quad (3)$$

$$W_{mit} \le \sum_{k=1}^{L}\sum_{o:r_{it}=o} G_{omk} \qquad \forall\, m, i, t \quad (4)$$

$$\sigma_{mkt} \le \sum_{i=1}^{M}\sum_{o:r_{it}=o} G_{omk} \qquad \forall m, k, t \quad (5)$$

$$\sum_{k=1}^{L} \sigma_{mkt} \le R \qquad \forall m, t \quad (6)$$

$$X_{mkt} \ge \sigma_{mkt} - \sigma_{mkt-1} \qquad \forall\, m, k, t = 2, \dots, T \quad (7)$$

$$Y_{mkt} \ge \sigma_{mkt-1} - \sigma_{mkt} \qquad \forall\, m, k, t = 2, \dots, T \quad (8)$$

$$F_{ijj_1t} \le \sum_{m=1}^{Z}\sum_{k=1}^{L}\sum_{o:r_{it}=o} G_{omk}\cdot MAC_{mj} \qquad \forall i, j, j_1, t = 1, \dots, T-1 \quad (9)$$

$$F_{ijj_1t} \leq \sum_{m=1}^{Z} \sum_{k=1}^{L} \sum_{o:r_{it+1}=o} G_{omk} \cdot MAC_{mj_1} \qquad \forall i,j,j_1,t = 1,\dots,T-2 \qquad (10)$$

$$W_{mit} \leq \sum_{j=1}^{N} \sum_{j_1=1}^{N} F_{ijj_1t} \cdot MAC_{mj} \qquad \forall i,m,t = 1,..,T-1 \qquad (11)$$

$$W_{miT} \leq \sum_{j=1}^{N} \sum_{j_1=1}^{N} F_{ijj_1T-1} \cdot MAC_{mj_1} \qquad \forall i,m \qquad (12)$$

$$\sum_{j=1}^{N} \sum_{j_1=1}^{N} F_{ijj_1t} = 1 \qquad \forall i,t = 1,..,T-1 \qquad (13)$$

$$\sum_{j_1=1}^{N} F_{ij_1j\,t} = \sum_{j_1=1}^{N} F_{ijj_1t+1} \qquad \forall i,j,t = 1,\dots,T-2 \qquad (14)$$

$$\sum_{k=1}^{L} \left(X_{mkt} \cdot \lambda_{mk} + Y_{mkt} \cdot \mu_{mk} \right) + \sum_{i=1}^{M} \sum_{o:r_{it}=o} (W_{mit} \cdot \tau_{om} \cdot \delta_i) \leq \xi \qquad \forall m,t \qquad (15)$$

$$F_{ijj_1t} \ binary \qquad \forall j,j_1,t \qquad (16)$$

$$W_{imt} \ binary \qquad \forall i,m,t \qquad (17)$$

$$\sigma_{mkt}, X_{mkt}, Y_{mkt} \ binary \qquad \forall m,k,t \qquad (18)$$

(2) ensures that each part batch in each period is processed by only one RMT. (3) guarantees the presence of module *k* on RMT *m* in period *t* if the module is required to perform the current operation. (4) allows the presence of the batch of part *i* on RMT *m* in period *t* if the required module *k* is available on that RMT, while (5) forces the presence of module *k* on RMT *m* in period *t* if the batch to work requires the module. (6) sets the maximum number of auxiliary modules that can be simultaneously assembled per RMT and time period. (7)-(8) set the auxiliary modules assembly and disassembly processes on/from RMTs. (9)-(10) admit the existence of flows of part *i* from cell *j* to cell j_1 if the required RMT and modules are present in the initial and final cell. (11)-(12) link the variables W_{mit} and F_{ijj_1t}, while (13)-(14) guarantee the continuity of part flow along their work cycle. (15) force not to exceed the available working time. Finally, (16)-(18) give consistence to the decisional variables.

3.3.2 Case study

The proposed model is applied to a relevant case study frequently adopted in the CM literature and representative of an operative industrial context (King, 1980, Gupta and Seifoddini, 1990, Bortolini et al., 2011). The problem is based on a 43 x 16 incidence matrix (number of parts x number of operations) (Gupta and Seifoddini, 1990, Bortolini et al., 2011). The work cycles and the daily target production volumes, together with data concerning the auxiliary module assembly and disassembly times, are outlined in Table B1 and Table B2 of Appendix B. The RMCs are 5 and a library of 10 auxiliary modules is available. In this phase, each RMT is assigned to a RMC, i.e. one machine per cell. The effect of different RMT aggregations will be analyzed and discussed in the next Section 4. Consequently, the initial RMT-RMC assignment is as follows: RMT #1 is in RMC #1, RMT #2 is in RMC #2, RMT #3 is in RMC #3, RMT #4 is in RMC #4 and RMT #5 is in RMC #5. In addition, it is supposed that each RMT has a specific level of reconfigurability, which affects the number of modules technologically compatible with that RMT. Three classes are considered.

- High level of reconfigurability, i.e. all the available auxiliary modules (100%) can be assembled;
- Mid level of reconfigurability, i.e. up to 50% of the modules can be assembled;
- Low level of reconfigurability: i.e. up to 33% of the auxiliary modules can be assembled.

The RMT-module and the operation-RMT-module compatibility matrices are in Table 12 and Table 13. Table 12 specifies the reconfigurability level of each RMT together with the auxiliary modules that can be assembled on each RMT, e.g. RMT #4 is characterized by low level of reconfigurability and auxiliary modules 1, 7 and 10 can be assembled. Table 13 reports the set of RMTs suitable for the execution of each operation together with the required auxiliary modules, in round brackets, and the unitary processing times in seconds, in squared brackets, e.g. Op3 can be executed on RMT #1 equipped with auxiliary module 5 with an unitary processing time of 8 seconds.

Table 12: RMT – module compatibility matrix

		Auxiliary modules									
RMT	Reconfigurability class	$k = 1$	$k = 2$	$k = 3$	$k = 4$	$k = 5$	$k = 6$	$k = 7$	$k = 8$	$k = 9$	$k = 10$
$m = 1$	High	1	1	1	1	1	1	1	1	1	1
$m = 2$	Medium	0	1	1	0	0	1	1	0	1	0
$m = 3$	High	1	1	1	1	1	1	1	1	1	1
$m = 4$	Low	1	0	0	0	0	0	1	0	0	1
$m = 5$	Medium	1	0	0	1	1	0	0	1	0	1

Table 13: Operation - RMT – module compatibility matrix

Operations (o)	(auxiliary modules) – [processing times in seconds]				
	$m = 1$	$m = 2$	$m = 3$	$m = 4$	$m = 5$
Op1	(1) – [12]		(1, 10) – [7]		(10) – [10]
Op2		(3, 9) – [7]			(5) – [9]
Op3	(5) – [8]	(2) – [11]		(1, 10) – [12]	
Op4	(4) – [11]	(3, 6) – [6]		(1) – [6]	
Op5		(7) – [9]		(7, 10) – [8]	(4, 8) – [11]
Op6	(3, 4) – [7]			(7) – [7]	
Op7	(2, 4, 9) – [10]		(8, 9) – [11]		
Op8		(2, 3, 6) – [12]	(3, 5) – [10]		
Op9			(4) – [12]		(4, 8) – [7]
Op10	(8) – [8]			(1) – [10]	(4, 5) – [12]
Op11		(6) – [7]	(2, 6) – [6]		
Op12		(6, 9) – [6]	(6) – [8]		
Op13	(10) – [8]		(1, 6, 8, 10) – [16]		(1, 10) – [11]
Op14	(1, 9) – [6]			(1, 7) – [11]	
Op15	(4, 6, 8) – [9]	(2, 3, 6, 7, 9) – [19]			(4, 8) – [9]
Op16		(2, 3, 7) – [10]	(1, 5, 9) – [8]	(1, 7) – [7]	(1, 4, 5, 10) – [24]

Table 14 shows the matrix containing the intercellular travel times, i.e. the time move a batch of part i from RMC j to RMC j_1, expressed in minutes.

Table 14: Intercellular travel time, minutes

Cell Id.	RMC #1	RMC #2	RMC #3	RMC #4	RMC #5
RMC #1	-	2	18	11	22
RMC #2	2	-	18	6	16
RMC #3	18	18	-	19	8
RMC #4	11	6	19	-	17
RMC #5	22	16	8	17	-

Finally, the available time per RMT and period, i.e. ξ, is of two shifts of 8 hours each and a maximum of 20 modules can be simultaneously assembled on each RMT. Given a planning horizon of about 840 periods, i.e. 840 working days, the set of the input data leads to 631,860 decisional variables and 31,648,242 constraints. The model is coded in AMPL language and processed adopting Gurobi Optimizer© v.4.0.1.0 solver on an Intel® Core™ i7 CPU @ 2.40GHz and 8.0GB RAM workstation. The global solving time is of about 50 seconds. The key results for the outlined scenario are summarized in the next sub-section 3.3.2.1.

3.3.2.1 Results and discussion

This paragraph proposes the main results obtained by adopting the proposed CRMS design model to the introduced industrial case study. At first, the minimization of the objective function ψ leads to an impact of the intercellular flows up to 86.7% (9589 flows equal to 908 hours) and of the auxiliary module installation, in terms of assembly and disassembly processes, up to 13.3% (138 hours). In particular, the auxiliary modules assembly time is 7.6% (79 hours) of the total time, while the disassembly time is the 5.7% (59 hours). Table 15 shows the intercellular flows among the five machine cells, i.e. RMCs. Each flow corresponds to the shipment of a batch of parts at the end of a working period.

Table 15: Number of intercellular flows

Cell Id.	RMC #1	RMC #2	RMC #3	RMC #4	RMC #5
RMC #1	-	3078	6	30	0
RMC #2	3059	-	0	99	189
RMC #3	39	0	-	73	735
RMC #4	16	152	83	-	550
RMC #5	4	115	762	599	-

Despite most of the flows are between near RMCs (see Table 14 for the unitary travelling times), e.g. RMC #1 and #2, the intercellular flows highly impact on the value of the objective function, i.e. 86.7%, stating the convenience to move the parts to RMCs already equipped with the required auxiliary modules rather than to remain on the same RMT changing its configuration.

Focusing on the five RMTs, Figure 20 shows the frequency diagrams of their use. Particularly, each graph focuses on an RMT and it presents the percentage of time periods the RMT works a mix of part types with the size indicated on the x-axis. This analysis is conducted by post-processing the variables W_{mit}, which denote the RMTs on which part types are processed in each time period.

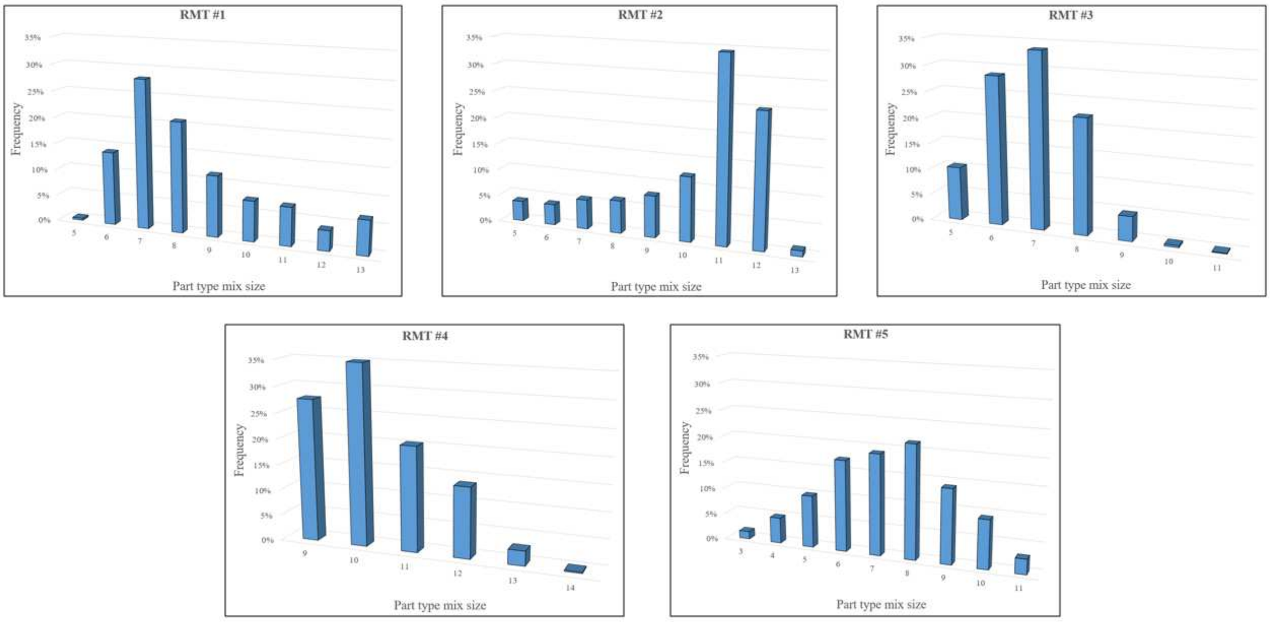

Figure 20: RMT use frequency diagrams

As example, in most of the periods, seven part types are processed by RMT #1 and RMT #3, eleven part types on RMT #2, ten part types on RMT #4 and eight part types on RMT #5. Because of, within the same period, the RMT configuration remains the same, i.e. auxiliary modules are changed between each couple of consecutive periods, only, high frequency of mixes with big sizes means the effective management of the auxiliary modules to create useful RMT structures for a wide set of work phases to be done at that time.

Figure 21 highlights the configuration of each RMT presenting the frequencies of installation of the number of auxiliary modules indicated on the *x-axis*. This analysis is conducted by post-processing the variables σ_{mkt}, which denote the RMTs on which auxiliary modules are located in each time period.

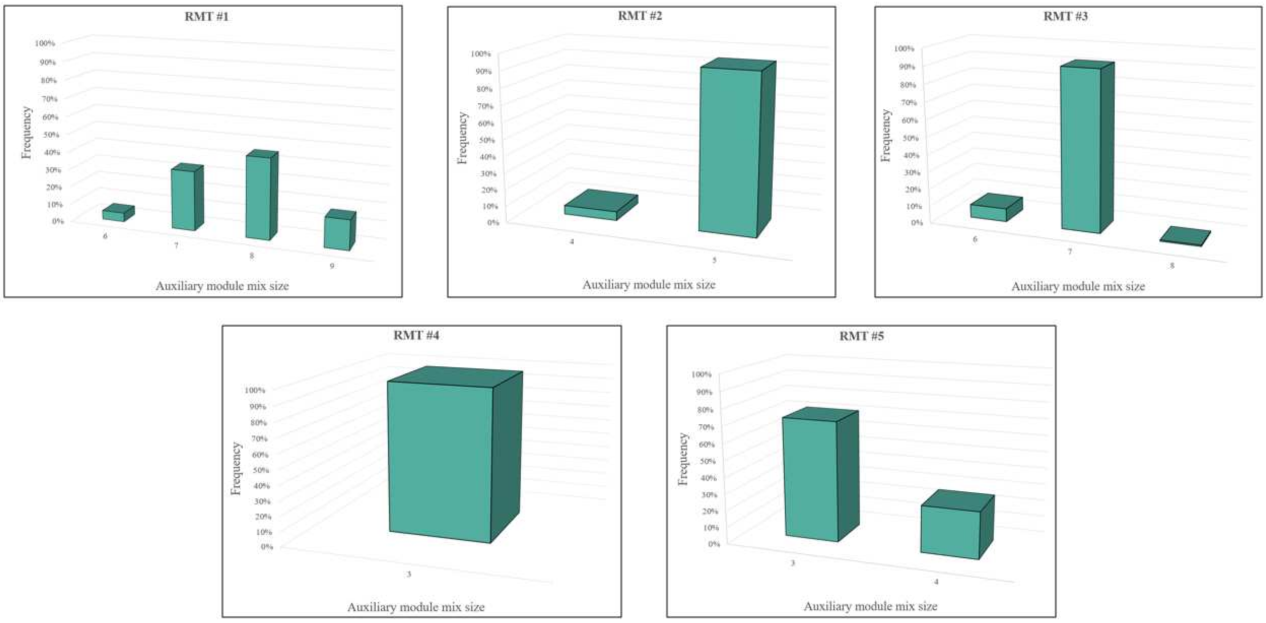

Figure 21: Auxiliary modules – RMTs allocation over the considered time horizon

In most of the periods, eight auxiliary modules are assembled on RMT #1, five auxiliary modules on RMT #2, seven auxiliary modules on RMT #3 and three auxiliary modules on RMT #5. Finally, three auxiliary modules (not always the same ones) are always on RMT #4.

3.3.2.1.1 Benchmarking

To benchmark the results highlighting a global convenience, the CRMS is compared against a conventional CMS, not including the auxiliary modules as elements of reconfigurability. The benchmark solution is introduced by Bortolini et al. (2011) considering the same input data. Key comparisons are in Table 16.

Table 16: Number of intercellular flows

	Intercellular travel time [h]	Module assembly and disassembly time [h]	Total time [h]	Saving
Conventional CMS	2193.57	0	2193.57	56.33%
CRMS	908.68	49.15	957.83	

Compared to the rigid system, the implementation of the CRMS shows relevant benefits in terms of reduction of the global intercellular travel time (-58.6%) despite the rising time needed to assemble and disassemble the auxiliary modules. The global time saving is of about 56.33%.

To extend the results obtained by applying the model to the proposed case study, the next Section 4 presents a multi-scenario analysis varying the number of RMCs and the RMT-RMC assignment assessing the impact of these factors on the model outcomes.

3.3.3 Multi-scenario analysis

The multi-scenario analysis is performed to test the effect of different RMT-RMC configurations on the system performances, changing, in each scenario, both the number of the available RMCs, i.e. $j = 1, \dots, N$, and the RMT-RMC assignment, i.e. MAC_{mj}. Such inputs represent the most critical data in CRMS design and management.

The proposed model is solved considering a number of RMCs ranging from 1, i.e. all RMTs are in a unique cell, to the number of RMTs, i.e. one RMT per RMC. For each of these cases, the distances among the RMCs, affecting the intercellular travel time, are adapted to get an effective and continuous production system. To this purpose, the Stirling number of the 2nd kind in equation (19) (Rennie and Dobson, 1969) returns the number of ways in which a set of m elements, i.e. the RMTs, can be partitioned into n subsets, i.e. the RMCs.

$$S(m,n) = \frac{1}{n!} \cdot \sum_{\varphi=0}^{n} (-1)^{\varphi} \binom{n}{\varphi} (n - 1)^{m} \tag{19}$$

In the proposed case study, the number of RMTs is constant, i.e. $m = 5$, while the number of RMCs ranges from 1 to 5, i.e. $1 \leq n \leq 5$, leading to five Stirling numbers. Given each of them, the permutations of the RMTs within the set of the available RMCs are calculated to get the scenarios to test. Table 17 summarizes this phase leading to 541 scenarios.

Table 17: Number of intercellular flows

Partition Id.	*S(m,n)*	Stirling numbers of the 2nd kind	Permutations	# of scenarios
1	*S(5,1)*	1	1	1
2	*S(5,2)*	15	2	30
3	*S(5,3)*	25	6	150
4	*S(5,4)*	10	24	240
5	*S(5,5)*	1	120	120

3.3.3.1 *Findings and comparison*

For the sake of brevity, detailed results for each scenario are omitted. An example of the lists containing the objective function values for all scenarios of Partition 1 and 2 are respectively in Table B3 and B4 of Appendix B. Table 18 focuses on the best and the worst scenario for each of the five partitions showing the incidence of the travel time and the module assembly and disassembly time on the objective function.

Table 18: Number of intercellular flows

		Best case configuration			Worst case configuration		Gap (%)
Partition Id.	ψ	Intercellular travel time (%)	Module assembly and disassembly time (%)	ψ	Intercellular travel time (%)	Module assembly and disassembly time (%)	
1	57	-	100	-	-	-	-
2	57	0	100	1563	95.86	4.14	-96.35
3	72	4.04	95.96	1728	94.80	5.20	-95.83
4	250	60.18	39.82	1853	91.67	8.33	-86.50
5	800	87.41	12.59	2030	95.22	4.78	-60.60

As example, the best configuration for Partition 3 corresponds to an impact of the intercellular flows on the objective function value up to 4.04% and of the module installation effort up to 95.96%. On the other side, the worst scenario stresses the intercellular flows (94.8%) toward the module installation effort (5.2%). Globally, the gap between these two opposite scenarios is of about 95.83%. Results allow concluding about the relevance of the problem addressed by the proposed model. For each partition, the relevant gap between the best and worst scenarios states the effect of wrong design choices in the RMT assignment to RMCs. In addition, the objective function values increase moving from Partition 1 to 5 guiding the designer in the case the number of RMCs becomes a free variable suitable to changes. Moreover, the proposed model considers more convenient the installation of the necessary auxiliary modules in presence of few RMCs, i.e. up to three. By increasing the RMCs, it becomes convenient mixing the module installation strategy and the part travel strategy. This is because the global time needed to continuously assemble and disassemble the auxiliary modules overcomes the time needed to move the part to a different RMT, located in another RMC, in which the required modules are ready. As in multiple industrial problems, given the set of efficient solutions, the decision-makers are asked to make the final choice best balancing the operative constraints and exogenous variables.

3.3.4 Concluding remarks

Nowadays, achieving high level of flexibility in production system design and management is a critical asset to compete. In Cellular Manufacturing Systems (CMSs) similar parts are grouped into families, and the corresponding machines into cells, to reduce lead times, setup time and work-in-process maintaining good levels of flexibility. Traditional CMSs show limits in adapting themselves to the emerging industrial and market trends, i.e. dynamic demand, fluctuating volumes and high-customized variants. In particular, given the cells, the physical relocation of the manufacturing tools to react to new production requirements becomes difficult. To overcome such rigidness, an emerging research stream explores the integration between CMSs and reconfigurable manufacturing paradigm leading to the concept of Cellular Reconfigurable Manufacturing Systems (CRMSs).

This study presents and applies an original integer linear programming model to design and manage CRMSs in a multi-product and multi-period environment best-balancing the part flows among machines ready to process them and the effort to install the necessary modules on the current machine. This problem is new and, to the Author's knowledge, it has never been explored by the literature. The proposed optimal procedure is applied to a relevant case study, made of an instance inspired from the literature, while a multi-scenario analysis widens the paper perspective assessing the impact of different machine-cell configurations on the system performances. Given the increasing customer request for different product variants in variable production batch sizes, this model can be effectively used by industry and practitioners in CMS environments to achieve reconfigurability and to support the decision-makers in defining the number of cells and their configurations. Future research deals with the extension of the model to include relevant issues not considered at this stage, e.g. auxiliary module availability, economic assessment, etc., as well as the application to larger industrial instances.

3.4 EVALUATION OF SAFETY, ERGONOMICS AND HUMAN FACTORS RELATED PERFORMANCES IN CRMS

Despite their automation level, CRMSs require actions to be performed directly by human workers rising relevant safety-, human factors- and ergonomics-related issues. As literature lacks of studies in this field, the aim of this section is to present a new methodological and operative framework supporting the integration of safety, ergonomics and human factors in the emerging reconfigurable manufacturing. Figure 22 shows a structured representation of the proposed methodology. The main ability of the methodology is to identify the main activities to be performed in a cellular reconfigurable manufacturing environment requiring manual operations and to combine these actions to specific Health and Safety (HS) critical areas, i.e. safety, manual handling tasks, working postures, and fatigue and stress.

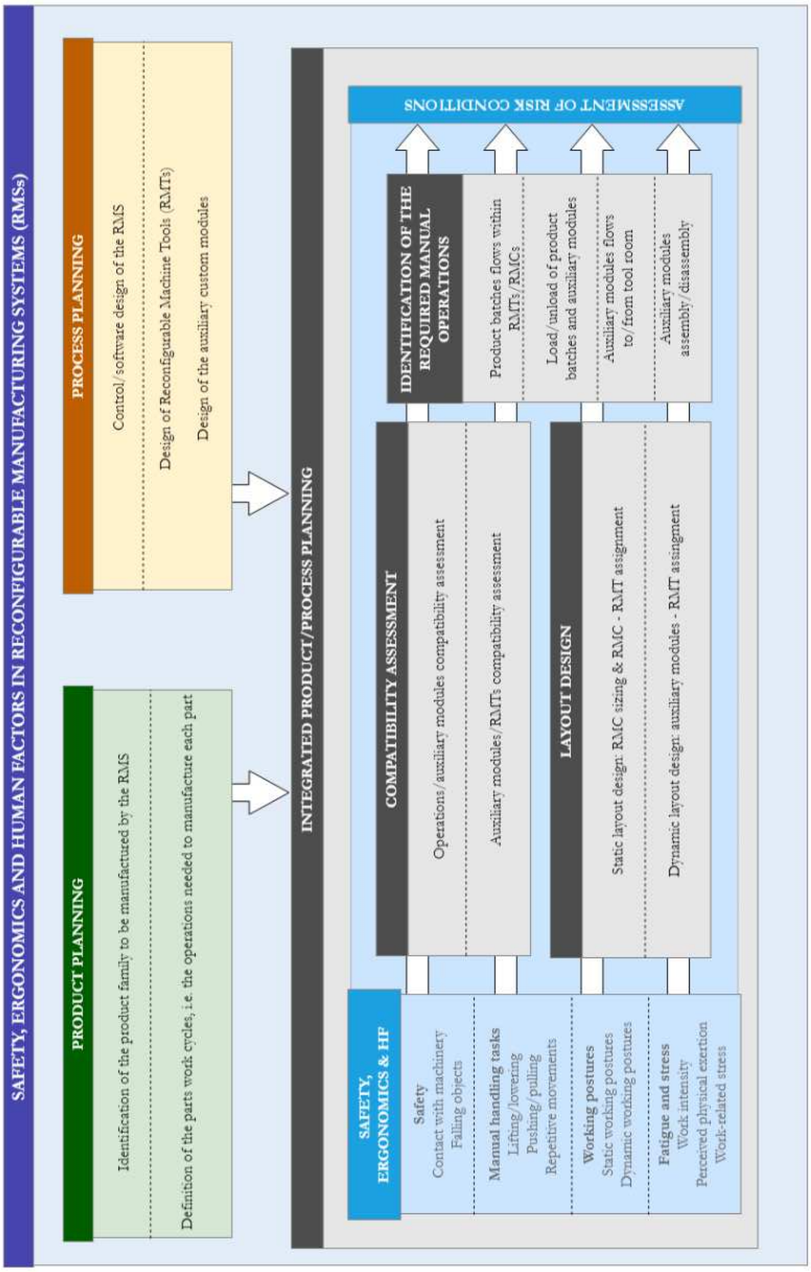

Figure 22: The proposed methodological framework

The proposed framework is organized into three main parts: product planning, process planning, integrated product/process planning.

3.4.1 Product planning

CRMSs are designed to produce a set of product families (Xiaobo et al., 2000, Galan et al., 2007). Following this concept and according to the standard literature within CRMS design and modelling, the first step to perform for an effective design of such systems is the definition of the product families that will be manufactured by the system itself. Each variant belonging to a product family will have a specific work cycle, i.e. the set of operations needed to manufacture the part. The operations will be performed on the available machines, i.e. RMTs, by using specific auxiliary custom modules.

3.4.2 Process planning

Once determined the set of product families that will be manufactured by the system, the second step suggested by the proposed framework is the hardware/software design of the system itself. In particular, the software design deals with the control design of the CRMS in terms of Programmable Logic Controller (PLC) programming while the hardware design deals with the design of RMTs and of the library of auxiliary modules.

3.4.3 Integrated product/process planning

The core of the proposed methodology for the integration of safety, ergonomics and human factors in RMSs is the third section of the proposed framework. In this phase, a symbiosis between the products and the process exists because the system reconfigures its hardware and software structure to accommodate the needs of the part work cycles. Safety, ergonomics and human factors principles are the driving factors of such symbiosis during the design of the RMS. Two main sub-phases have been identified:

a) *compatibility assessment*: this phase provides answers to the following two key questions: *"Which auxiliary module (or combination of modules) is needed to perform a specific operation?"* and *"On which RMT/RMTs can the auxiliary modules be assembled?* This means that the part operations can be performed only on the RMTs that show technological compatibility with the required auxiliary modules.

b) *layout design*: in this phase the layout of the CRMS is defined from a static and dynamic perspective. The static design deals with the RMCs sizing as well as the assignment of RMTs to each RMC. The dynamic layout deals with the assignment of the auxiliary custom modules to each RMT. In particular, in this step it is interesting to best-balance the part flows among RMCs and the effort to install the auxiliary modules on the RMT on which the part is located. This trade-off is crucial and gives dynamism to the industrial setting because in each time period RMTs can take a different layout in terms of auxiliary modules.

The proposed methodology supports industrial companies in identifying the main activities requiring manual operations. Such operations include the product batches flows within the RMTs or the RMCs, the loading and unloading of product batches and auxiliary modules, the activities dealing with the auxiliary modules flows to/from the tool room, and the manual assembly/disassembly of the auxiliary modules. RMS designers are required to ensure the HS conditions of the manual workers involved in the manufacturing process. The framework in Figure 1 shows a focus on "Safety, Ergonomics and Human Factors" suggesting a set of HS critical areas to be addressed during the design of a RMS. The framework shows that in a RMS environment all the identified HS critical areas have a direct impact on the identified manual operations.

The first HS critical area deals with safety issues as the contact of the worker with the machinery and the risk of falling objects. Design may refer to ISO standards on safety of machinery describing the principles for safety in machinery design, e.g. ISO 13849 Parts 1 and 2, ISO 13851, ISO 13856 Parts 1 and 2, and the ISO 12100 Series (International Standard Organization, 2009, 2010, 2012, 2013a, 2013b). Specifically, the 12100:2010 (International Standard Organization, 2010) is a type-A safety standard which describes a methodology for achieving safety in the design of machinery. Such standard specifies the principles of risk assessment and reduction aiming to help designers in the achievement of safety. Furthermore, procedures are defined for identifying hazards and assessing risks during the machine life cycle, and for the hazards elimination or, in case this is not possible, for the risk reduction.

The second HS critical area addresses the analysis of manual handling tasks, including lifting and lowering, pushing and pulling and repetitive tasks. RMS designers are encouraged to apply the ergonomics standards on manual handling, e.g. the ISO 11228-1 for lifting and lowering (International Standard Organization, 2003), the ISO 11228-2 for pushing and pulling (International Standard Organization, 2007b) and the ISO 11228-3 for repetitive movements (International Standard Organization, 2007a). These standards are not regulatory requirements. However, the application of the best practices prevents manual handling injuries and other losses due to unsafe or improper manual handling. In 2014, the publication of the Technical Report ISO/TR 12295 provided a critical support to employers, ergonomists and other practitioners in the selection and use of the 11228 series of International Standards (International Standard Organization, 2014). This technical report provides a *quick assessment* methodology supporting the identification of *certainly acceptable* or *certainly critical* manual handling activities. *Certainly acceptable* activities do not require any corrective action. *Certainly critical* activities require the immediate reduction of the risk, following the directions in the relevant standards on manual handling. Activities, work processes and/or workplaces should be re-designed, according to the priorities revealed during the risk assessment. Where the *quick assessment* shows the presence of a risk between the two boundary conditions, then it is necessary to apply the detailed risk assessment methodologies in the relevant standard.

The third HS critical area investigates the working postures assumed by the workers during manual operations at the RMSs. Static and dynamic working postures should be analyzed, aiming to identify potential risks for workers' HS. Static working postures refer to physical exertion in which the same posture or position is held for more than 4 seconds (International Standard Organization, 2000). Dynamic working postures refer to posture and positions assumed while performing a movement. The ISO 11226 is the reference standard for the evaluation of static working postures (International Standard Organization, 2000). The European Standard EN 1005-4 describes the approach to the evaluation of dynamic working postures, as the working postures and movements in relation to machinery. Specifically, this European Standard supports designers when designing machinery or its component parts in assessing and affecting health risks due only to machine-related postures and movements, i.e. during assembly, installation, operation, adjustment, maintenance, cleaning, repair, transport, and dismantlement (European Committee for Standardization, 2008). The requirements of both the ISO 11226 and the EN 1005-4 are intended to reduce the health risks due to awkward working postures for nearly all healthy adults.

The last HS critical area focuses on fatigue and stress. RMS designers are encouraged to investigate the working conditions that may increase workers' fatigue and stress. Work intensity, the level of perceived physical exertion and work-related stress should be assessed at this stage. A recognized quantitative methodology for the rating of perceived exertion is the Borg rating of perceived exertion scale (Borg, 1982). The research on occupational medicine have widely investigated the relationship between physical load an physiological responses, as well as the relationship between mental load and perceptual responses (Borg, 1990). Mentally stressing situations are commonly investigated by means of physiological indicators of the degree of strain. However, perceptual indicators of physical strain, e.g. the Borg scale, should be adopted as well (Borg, 1990).

3.4.4 Concluding remarks

In the last few years, the concept of reconfiguration in the field of manufacturing systems raised considerable interest in the academic and industrial communities. Reconfigurable Manufacturing Systems (RMSs) represent a new type of manufacturing system, which focus on increasing the system responsiveness to fluctuating and dynamic market and enabling an efficient competition in modern volatile markets. Such systems require different layout configurations switching by one product family to another and, usually, are organized in working cells, leading to the concept of Cellular Reconfigurable Manufacturing Systems (CRMSs). During the years, several studies have been published proposing innovative methods and tools for the design and management of CRMSs. However, many open questions remain and several practical challenges represent fertile areas of research. Among these, the impact on safety, ergonomics and human factors coming from the switch to such emerging systems is not yet widely studied. Indeed, despite their high level of automation, RMSs require actions to be performed directly by human operators as material handling, WIP load/unload and tool setup, making necessary the design of industrial settings, which are healthy and safe for human workers. This chapter fills this gap defining a practical methodological and operative framework supporting the integration of safety, ergonomics and human factors in the new RMS paradigm. The proposed methodology identifies the activities to be performed in a RMS environment requiring manual operations and combines such activities to specific Health and Safety (HS) critical areas, i.e. safety, manual handling tasks, working postures, and fatigue and stress, supporting academic, industrialist and practitioners in designing reconfigurable manufacturing systems, which are efficient from both the technical and ergonomic perspectives.

Next Chapter 4 investigates the introduction of reconfigurability principles switching from the manufacturing to the assembly domain with the aim to design advanced assembly systems which are rapidly real-time reconfigurable according to product features, e.g. size, work cycle, and human operator features, e.g. anthropometric measurements.

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Appendix B

Table B1: Part work cycles and production volumes

Part (i)	δ_i[pcs/period]	Work cycle
1	50	Op6-Op10-Op7-Op8-Op6
2	150	Op2-Op9-Op6-Op9-Op8-Op16-Op14-Op2
3	500	Op8-Op13-Op11-Op8
4	75	Op9
5	500	Op4-Op15-Op5-Op4
6	1200	Op6-Op14
7	1500	Op3-Op6-Op16-Op3
8	750	Op8-Op5-Op6
9	5000	Op4-Op11-Op5-Op8-Op4
10	1300	Op9-Op2-Op16
11	1239	Op8-Op12
12	575	Op8-Op6-Op10-Op8
13	1239	Op7-Op6-Op10
14	1500	Op4-Op6-Op5-Op6
15	14000	Op5-Op8
16	39	Op5
17	900	Op3-Op14-Op6-Op3
18	339	Op9-Op16
19	390	Op4-Op6-Op8-Op5-Op6-Op15
20	304	Op8-Op11
21	405	Op4-Op8-Op5-Op15-Op4
22	1200	Op5-Op12
23	5	Op4-Op6-Op5-Op8
24	35	Op8-Op11-Op13-Op12-Op8
25	390	Op7-Op10
26	750	Op10
27	39	Op11-Op12-Op8
28	320	Op2-Op9-Op8
29	1500	Op4-Op5
30	11300	Op11-Op12
31	310	Op8-Op10
32	430	Op2-Op9-Op6-Op16-Op9
33	500	Op5-Op15-Op6-Op5
34	275	Op3-Op6
35	500	Op14-Op3
36	600	Op3
37	1500	Op1-Op2-Op9-Op8-Op6-Op16-Op9
38	750	Op2-Op9-Op8-Op16-Op9
39	5000	Op6-Op10
40	1300	Op9-Op2-Op6-Op9
41	1239	Op5-Op8-Op15
42	575	Op1-Op2-Op9-Op6-Op2-Op16-Op1

43	1239	Op5-Op6-Op8-Op15-Op6

Table B2: Auxiliary module assembly and disassembly time (minutes)

Machine	Module	λ	μ
1	1	3.32	2.49
1	2	3.73	2.79
1	3	3.56	2.67
1	4	3.94	2.95
1	5	3.92	2.94
1	6	3.41	2.55
1	7	3.46	2.59
1	8	4.22	3.16
1	9	4.03	3.02
1	10	4.41	3.30
2	1	-	-
2	2	4.22	3.16
2	3	6.1	4.57
2	4	-	-
2	5	-	-
2	6	5	3.75
2	7	4.7	3.52
2	8	-	-
2	9	6.02	4.51
2	10	-	-
3	1	3.9	2.92
3	2	7.2	5.4
3	3	9	6.75
3	4	8.6	6.45
3	5	9.2	6.9
3	6	7.75	5.81
3	7	4.15	3.11
3	8	5.1	3.82
3	9	6.2	4.65
3	10	8.5	6.37
4	1	4.6	3.45
4	2	-	-
4	3	-	-
4	4	-	-
4	5	-	-
4	6	-	-
4	7	8.87	6.65
4	8	-	-
4	9	-	-
4	10	10.2	7.65
5	1	9.4	7.05
5	2	-	-
5	3	-	-
5	4	9.1	6.82
5	5	15	11.25
5	6	-	-

5	7	-	-
5	8	8.8	6.6
5	9	-	-
5	10	12	9

Table B3: RMT assignment, in squared brackets, and objective function value for partition 1, i.e. one RMC

RMT-RMC assignment	
RMC#1	Objective function value [h]
[1 2 3 4 5]	57

Table B4: RMT assignment and objective function values for partition 2, i.e. two RMCs

RMT-RMC assignment		
RMC#1	RMC#2	Objective function value [h]
[5]	[1 2 3 4]	90
[1 2 3 4]	[5]	90
[4]	[1 2 3 5]	57
[1 2 3 5]	[4]	57
[4 5]	[1 2 3]	90
[1 2 3]	[4 5]	90
[3]	[1 2 4 5]	65
[1 2 4 5]	[3]	65
[3 5]	[1 2 4]	595
[1 2 4]	[3 5]	595
[3 4]	[1 2 5]	65
[1 2 5]	[3 4]	65
[3 4 5]	[1 2]	101
[1 2]	[3 4 5]	101
[2]	[1 3 4 5]	57
[1 3 4 5]	[2]	57
[2 5]	[1 3 4]	533
[1 3 4]	[2 5]	533
[2 4]	[1 3 5]	65
[1 3 5]	[2 4]	65
[2 4 5]	[1 3]	107
[1 3]	[2 4 5]	107
[2 3]	[1 4 5]	1563
[1 4 5]	[2 3]	1563
[2 3 5]	[1 4]	1329
[1 4]	[2 3 5]	1329
[2 3 4]	[1 5]	752
[1 5]	[2 3 4]	752
[2 3 4 5]	[1]	178
[1]	[2 3 4 5]	178

4 DESIGN AND MANAGEMENT OF RECONFIGURABLE ASSEMBLY SYSTEMS

This chapter addresses the *RQ. 3* focusing on the introduction of reconfigurability principles in the assembly domain aiming at designing advanced assembly systems which are rapidly real-time reconfigurable according to product features, e.g. size, work cycle, and human operator features, e.g. anthropometric measurements. To this aim, a conceptual framework is defined to support industrial companies to achieving real-time manual and automatic reconfiguration of such systems. The proposed framework is, then, applied to a real prototypal assembly cell, called Self-Adaptive Smart Assembly System. An easy-to-use GUI and a tool based on the use of 3D sensing devices, i.e. Microsoft Kinect™, are developed to allow an efficient assembly system reconfiguration. The content is based on the following research papers: (1) Cohen, Y., Faccio, M., Galizia, F. G., Mora, C., Pilati, F. (2019). Assembly system configuration through Industry 4.0 principles: the expected change in the actual paradigms, *IFAC-PapersOnLine*, 50(1), 14958-14963, (2) Bortolini, M., Accorsi, R., Faccio, M., Galizia, F. G., Pilati, F. (2019). Toward a real-time reconfiguration of self-adaptive smart assembly systems, *Procedia Manufacturing*, in press, (3) Bortolini, M., Faccio, M., Galizia, F. G., Gamberi, M., Pilati, F. (2019). Design, engineering and testing of an innovative adaptive automation assembly system, *Assembly Automation*, under review.

Manufacturing is the backbone of the global economy. Currently, more than 27 million people are employed in 230.000 manufacturing companies, creating, in the EU area, a total added value of about € 1,300 million (Westkämper, 2007). In this context, Industry 4.0 (I4.0) emerged as the fourth industrial revolution, enhancing the manufacturing and assembly paradigms and driving them on the way to a knowledge-based and digital era (Ghobakhloo, 2018). The final challenge is to create the so-called Smart Factory, an intelligent industrial context in which all the elements are integrated together and communicate in real-time (Nascimento et al., 2018, Rachinger et al., 2018). According to the Boston Consulting Group, I4.0 includes nine enabling technologies to support the paradigm implementation in industry (Rüßmann et al., 2015). Table 19 lists and describes them.

Table 19: Industry 4.0 enabling technologies

Id.	Enabling technology	Description
1		Autonomous, cooperating industrial robots

	Advanced Manufacturing Solutions	Numerous integrated sensors and standardized interfaces
2	Additive Manufacturing	3D printing, particularly for spare parts and prototypes Decentralized 3D facilities to reduce transport distances and inventory
3	Augmented Reality	Augmented reality for maintenance, logistics Display of supporting information, e.g. through glasses
4	Simulation	Simulation of value networks Optimization based on real-time data from intelligent systems
5	Horizontal/Vertical Integration	Cross-company data integration based on data transfer standards Precondition for a fully automated value chain
6	Industrial Internet	Network of machines and products Multidirectional communication between networked objects
7	Cloud	Management of huge data volumes in open systems Real-time communication for production systems
8	Cyber-security	Operation in networks and open systems High level of networking between intelligent machines, products and systems
9	Big Data and Analytics	Full evaluation of available data (e.g. from ERP and machine data) Real-time decision-making support and optimization

Among these technologies, advanced manufacturing solutions, i.e. Id.1, have a direct impact on the modern manufacturing and assembly systems. This enabling technology refers to the set of flexible, smart and modularized manufacturing and assembly systems integrating sensors and standardized interfaces (Rüßmann et al., 2015). In particular, reconfigurable and changeable manufacturing and assembly systems falling in this category are equipped with actuators, sensors and control architectures to achieving elasticity and agility and to enabling the integration of real time data sources into service-oriented architectures (Mehrabi et al., 2000, Mehrabi et al., 2002, Andersen et al., 2018a, Andersen et al., 2018b, Bortolini et al., 2018).

This chapter focuses on assembly systems, representing the last phase of production. Manual assembly systems usually bring to high flexibility and low productivity if compared to fully automated systems (Fletcher et al., 2019). To increase productivity, maintaining flexibility, the future systems need to include greater levels of automation to complement the skills and capabilities of the human workers. Within the current literature, RASs rise as effective systems able to automatically modify themselves in response to changes in their reference operating environment (Huebscher and McCann, 2008, Krupitzer et al., 2015). These changes deal with adjustments of some of their hardware and software attributes. The increasing product variety asked by the market makes these systems of strong interest within mixed-model flexible manual assembly lines (Faccio, 2014, Faccio et al., 2015, Galizia et al., 2019). To successfully implement such systems with high adaptivity and

interactivity between human workers and technology, a comprehensive understanding of the design requirements is needed. However, lacks in practical solutions exist and applied research needs to propose innovative and effective design of such systems able to manage different product models characterized by different attributes in terms of parts, dimensions, tasks and production volumes.
The objective of this chapter is twofold: 1) to propose a conceptual schematic helping to achieving real-time manual and automatic reconfigurations of RASs, and 2) to apply this framework to a prototypal RAS, called Self-Adaptive Smart Assembly System (SASAS) in the following, highlighting its features and its potential impact on industry. In particular, the proposed prototype includes an easy-access fast-picking area for the fast-moving parts equipped with two motion axes to optimize its position, while a third motion axis allows the reconfiguration of the working area height. Its main element of innovation is the real-time reconfigurability according to the product features, the work phase and the operator features, allowing a reduction of the movements during the picking and assembly phases for both small and medium size products, i.e. gross volume up to $1.5m^3$. This is a relevant benefit due to the high number of operator movements both in the front and in the back positions especially in the pick & place phases. A quantitative field test of the improvements coming from the prototype use are in the lab experiment and in the industrial scenario sections. An Italian company assembling industrial refrigerators and including the prototype in each station of its mixed-model assembly line is involved in the study.
According to the introduced background and goals, the remainder of this chapter is organized as follows. Section 4.1 revises the literature on the topic while Section 4.2 presents the conceptual schematic helping achieving real-time reconfigurability in RASs. Section 4.3 presents and describes the SASAS prototype. Section 4.4 and 4.5 respectively focus on SASAS manual and automatic real-time reconfigurability proving the benefits in terms of productivity and ergonomics arising from its reconfiguration. Section 4.6 showcases the system use in the aforementioned relevant industrial scenario. Finally, Section 4.7 concludes this chapter with final remarks and future research opportunities.

4.1 LITERATURE REVIEW

This section is organized into two parts. The former explores the main factors involved in modern assembly systems considering both the station design and the component management policy, the latter presents the Industry 4.0 environment and its link to the emerging paradigms of smart and reconfigurable assembly systems.

4.1.1 Assembly system design and component management

Assembly represents the capstone process for product realization in which components and subassemblies are integrated together to get the final product (Hu et al., 2011). In the I4.0 context, based on the shift from mass production to mass customization, assembly workplaces have to evolve to maintain acceptable productivity standards as well as top working conditions for the human operators (Bortolini et al., 2017). Assembly activities, i.e. tasks, usually include several operations, e.g. component picking, walking, assembly task execution, etc. Previous research by Finnsgard et al. (2011), Finnsgard and Wänström (2013) and Wild (1975) find that picking covers a relevant portion of the cycle time, frequently higher than the 50% of the total time. The possibility to reduce this time, not immediately and directly adding value to the products, is of much interest and it is linked to the reduction of the operator movements and to the distance of the components to pick. To get this goal both the assembly station layout and the working conditions play a crucial role. Within the latter point, the choice of the part feeding policy is of major interest. The literature suggests three feeding modes, i.e. line stocking, kitting and sequencing (Sali et al., 2015). Sali et al. (2015) define them and propose a model to assess the associated operating costs. In addition, a multi-scenario analysis identifies the boundary conditions under which each of them is preferable. Limère et al. (2015) link the part storage place and the feeding policy to the amount of stock and the operator walking distance during assembly. Hanson et al. (2015) prove that the possibility of ranking parts according to the assembly needs significantly reduces the searching and sorting time. Globally, compared to the line stocking, in which parts are collected by reference in dedicated containers, the part kitting strategy increases the productivity and the assembly line availability due to ready-to-use kits of the components to mount at the same time. By adopting such strategy, less time is spent for searching and the training of the assemblers is easier (Limère et al., 2012). Furthermore, in the case of large and heavy parts, kitting is mandatory to reduce the space utilisation and the ergonomic impact of the assembly station activities (Battini et al., 2011). In this field, Bortolini et al. (2017) propose a multi-objective optimization model for the assembly line balancing problem (ALBP) minimizing the assembly line takt time and the ergonomic risk caused by the task execution and the component picking activities. Further efforts are from Bautista-Valhondo, Alfaro-Pozo (2018) and Tiacci and

Mimmi (2018) adopting multi-objective perspectives, optimal and heuristic approaches. All the Authors conclude about the strong connection between the assembly system layout and the component management policy encouraging further research in the field through comparative analyzes in industry.

4.1.2 The Industry 4.0 environment and its link with smart and reconfigurable assembly systems

I4.0 is changing the industrial environment, the manufacturing and assembly paradigms. The term "Industry 4.0" comes from a project on high-tech strategy promoted by the German government in 2011 to spread computerization in manufacturing (Lee et al., 2015) and, in the last years, it emerged as the fourth industrial revolution (Cohen et al., 2017). The concepts of Smart Factory (SF) and Smart Manufacturing (SM) drive this upcoming revolution, while augmented reality, Internet of Things (IoT), Cyber-Physical Systems and Cloud Technology are among the major technologies adopted in SF and SM (Kang et al., 2016; Yao and Lin, 2016). Radziwon et al. (2014) study the evolution of SFs analyzing the literature and define them as "manufacturing solutions that provide flexible and smart production processes to solve problems arising on a production plant rapidly changing boundary conditions in a world of increasing complexity". Similarly, SM is defined as "a set of various technologies able to promote a radical innovation of the existing manufacturing industry through the integration of humans, technology and real-time information" (Kang et al., 2016). The National Institute of Standards and Technology (NIST) defines SMs as "fully-integrated and collaborative manufacturing systems that respond in real time to meet the changing demands and conditions in the factory, supply network, and customer needs" (National Institute of Standard and Technology, 2015). In this new industrial environment, information are real-time collected and distributed to support human operators in their work (Tzimas et al., 2018). Fasth-Berglund and Stahre (2013) discuss the importance of considering both the physical and cognitive automation to handle the increased demand variability and to improve the social sustainability within the company. Chaplin et al. (2015) define an architecture for reconfigurable assembly systems to enhance the ability to react to changes in products, processes and market. Furthermore, Sand et al. (2016) present the so-called smARt.assembly – a projection-based augmented reality assembly assistance system for industrial applications to support human workers in picking activities eliminating the use of smart glasses. Tzimas et al. (2018) introduce a study on the use of augmented reality technologies to real-time give instructions to the operators supporting manufacturing tasks. Liu et al. (2017) analyze the characteristics of IoT-based manufacturing systems considering an intelligent assembly system for mechanical products as a case study to achieve the design optimization of the assembly process and the intelligent operation of the assembly system.

In the field of adaptive automation assembly systems, Rohr et al. (2006) outline some key directions of self-adaptation, i.e. origin, activation, system layer, controller, distribution, and operation. Salehie and Tahvildari (2009) introduce an overview of the landscape of self-adaptive software, including their own taxonomy for self-adaptation. In particular, the Authors introduce 5W + 1H questions for eliciting adaptation requirements: "When to adapt? Why do we have to adapt? Where do we have to implement change? What kind of change is needed? Who has to perform the adaptation? How is the adaptation performed?"

Finally, the recent literature states that industrial companies need to be educated and trained towards the adoption of the upcoming industrial paradigms. In this context, a strong collaboration between Academia and industry is crucial to spread the culture of innovation. The so-called "learning factories" are promising environments for research, training and education. They reproduce small smart and reconfigurable production and assembly systems and their use is proved to be beneficial to train industrial companies toward such advanced manufacturing and assembly systems (Abele et al., 2017; ElMaraghy, 2019). From this perspective, the proposed SASAS can be of help to set up future learning factories for assembly, highlighting the potential upgrades in terms of flexibility, productivity and operator ergonomics toward the current widely diffused industrial scenarios.

4.2 REAL-TIME RECONFIGURABILITY IN RECONFIGURABLE ASSEMBLY SYSTEMS

Next Figure 23 introduces a conceptual schematic helping to achieving real-time reconfiguration in RASs. Afterwards the focus is on the description of the main components characterizing the proposed prototype of SASAS.

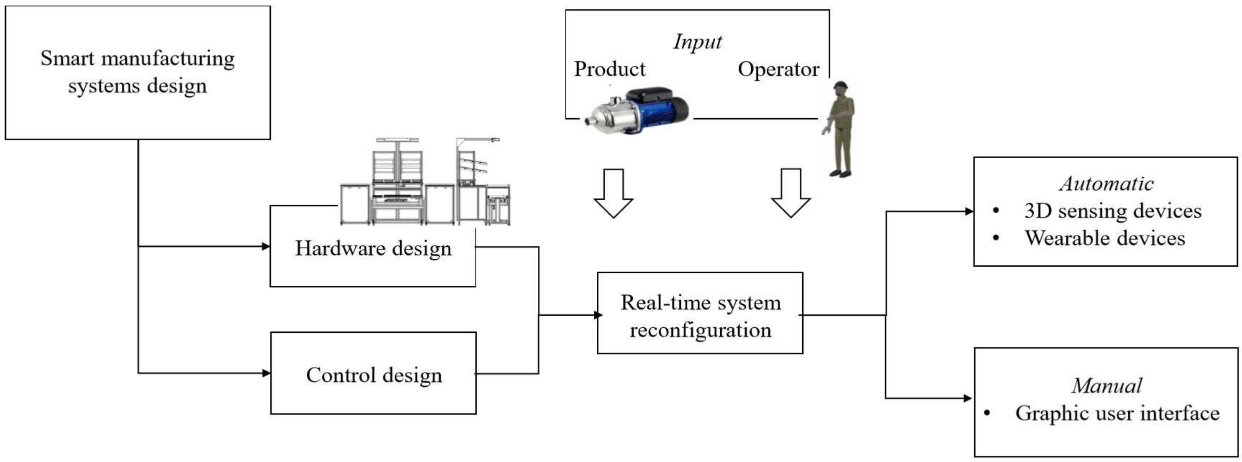


Figure 23: Conceptual schematic to achieve real-time reconfigurability in RASs

As in the above figure, once concluded the phases of hardware design and control design, in terms of Programmable Logic Controller (PLC) programming, it is possible to include reconfigurability issues in RASs. In particular, the main goal is to make the manufacturing system able to real-time reconfigure its hardware structure according to input data coming from the product, i.e. size, dimensions, work cycle, and from the human operator, i.e. anthropometric measurements. The real-time system reconfiguration can be automatically performed by using 3D sensing devices, i.e. depth cameras, wearable devices, or manually performed by using flexible Graphic User Interfaces (GUIs). The study proposed in this thesis addresses both issues. Specifically, the manual system reconfiguration based on product input data and human operator anthropometric measurements is achieved through the development of an easy-to-use GUI. The automatic system reconfiguration is performed relying only on the anthropometric measurements by using 3D sensing devices, i.e. Microsoft Kinect™.

4.3 ASSEMBLY PROTOTYPE DESCRIPTION

Figure 24 presents a CAD front and lateral view of the proposed prototype of SASAS, while Figure 25 shows the 3D layout, with a detail of the four functional modules, and a real picture of the prototype.

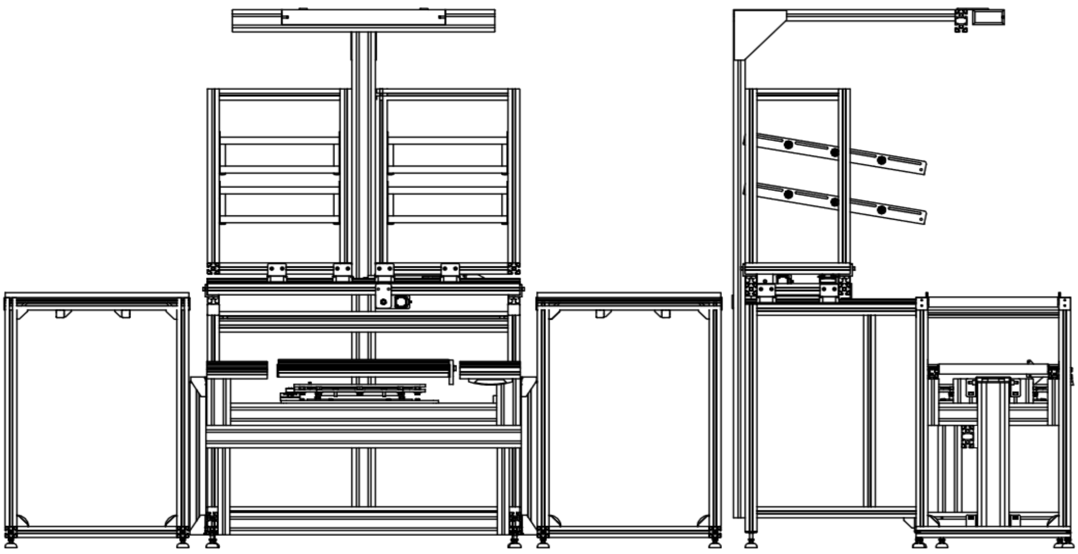


Figure 24: SASAS CAD model

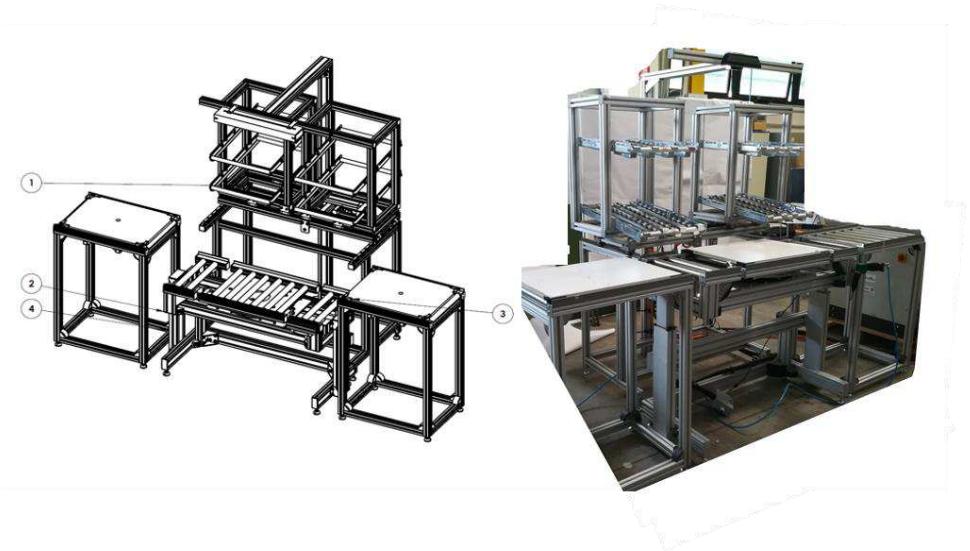


Figure 25: Components of the prototype: 1. Modules for the storage of the assembly parts and components; 2. Extendable supports of the main roller conveyor; 3. Lateral roller conveyor; 4. Main roller conveyor

The workstation consists of three roller conveyors, one in the central position on which the operator performs the assembly tasks (4), and two lateral units allowing the product flow (3). Thanks to two screw-nut groups driven by two digital motors (2), the central roller conveyor can translate vertically. When the work piece reaches this position, a set of spring-loaded devices locks the table on the main roller conveyor and a rotating mechanism located below the roller conveyor allows the rotation of the work piece table. The assembly components are stored in a fast-picking area (1) made of two modules containing the parts and components needed for the product assembly. Such two modules move along the two Cartesian axes, opening and closing symmetrically and moving toward the operator to ease the component pick. This mechanism overcomes the industrial practice, in which the components to assemble are usually placed behind the operator, and allows the reduction of the operator movements and, consequently, of the picking time. This functional module is designed according to the Ergonomics Guidebook for Manual Production Systems edited by Rexroth - Bosch Group (Rexroth, 2018). According to these guidelines, all containers, equipment and operating elements must be easily accessible and arranged in the anatomic/physiological range of movement of the operator (Figure 26). Furthermore, torso rotations and shoulder movements, particularly when under exertion, are avoided.

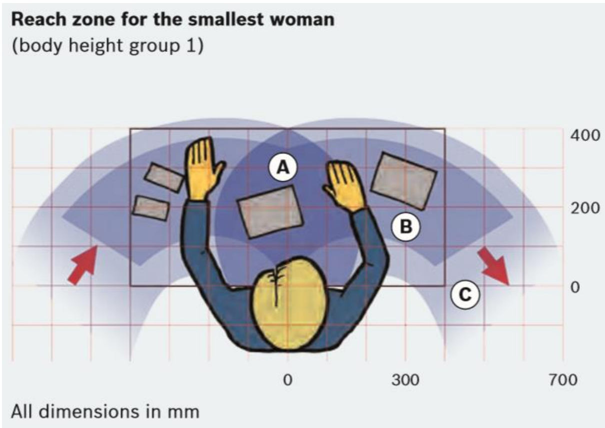


Figure 26: Reach zones classification, derived by Bosch Ergonomics Guidebook (Rexroth – Bosch Group, 2018)

In Figure 26, Area A is suitable for working with both hands, Area B is an area for tools and components that are often grabbed with one hand, while Area C is for occasional handling. The benefits coming from such a design are (1) the reduction of operator discomfort and fatigue, (2) the reduction of operator movements and (3) the consequent reduction of the component picking time. The prototype information and control are real time managed by the system logic controller. The adopted PLC is a Bosch Rexroth XM model, accessed through Bosch IndraWorks Engineering software and connected to Matlab® development environment. Appendix C presents the pseudocode of the SASAS main control instructions together with the two functions called to act on the storage module position and the workplace height. The controller allows to synchronize the SASAS motion axes to the optimized work positions caught from external databases and listed, task by task, according to the operator features, e.g. physical body, skills, etc. and the product dimensions. After the axis initialization and the load of the work cycle, the controller cycles over the work phases and self-adapts the position of the workplace, i.e. #4 in Figure 25, and of the easy access storage modules, i.e. #1 in Figure 25. Controls on the feasibility of the axis movements are done to avoid collisions among the SASAS, the product and the operator. In case of potential danger, the system returns to a safe base position autonomously and a feedback is given to the operator. Otherwise, the transition between a work phase and the next one is managed automatically as soon as the operator acknowledges the end of the mounting activities of the current work phase. Thanks to the connection to a dynamic product library containing the product work cycles and operator features the SASAS is fully flexible and autonomous for its reconfiguration and real-time adaptation to the current working activities.

Finally, the SASAS prototype and its managing system are suitable to the assembly of small and medium size products characterized by an overall volume up to $1.5m^3$ having a depth value close to 400 mm and a width value up to 640 mm.

4.4 MANUAL REAL-TIME SYSTEM RECONFIGURATION

4.4.1 A Graphic User Interface (GUI) to aid real-time system reconfiguration

After the phase of PLC programming, an easy-to-use GUI is developed to allow the human operators to real-time reconfigure the systems according to their anthropometric measurements, to the product features and product work cycle. The proposed GUI is developed in Matlab® by using the Graphic User Interface Design Environment (GUIDE) tool and is composed by four main sections:

- Boot interface
- Setting
- Products
- New product

The main goal of the proposed GUI is to support the human operators in the real-time system reconfiguration and self-adaptability by storing information about the work cycles of products manufactured by the case company and associating each operation of the product work cycle to a specific movement/reconfiguration of the system components. The description of the GUI sections is in the following.

4.4.1.1 *Boot Interface*

This section is the first screen of the developed GUI, as in Figure 27. In this window, the CAD front and lateral view of the SASAS is shown together with the Academic institutions involved in the project.

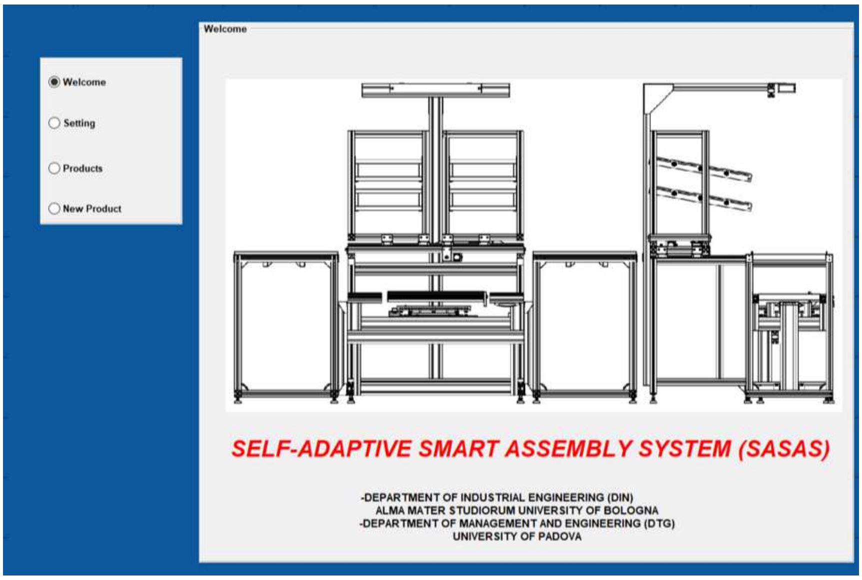


Figure 27: Boot Interface section of the developed GUI

4.4.1.2 *Setting window*

This section allows the manual setting of the SASAS motion axes, i.e. opening/closing of the fast-picking area and vertical moving of the central roller conveyor (Figure 28). When the human operator starts to perform the different operations required by the product work cycle, the fast-picking area has to be in the closing position and the central roller conveyor set to a height of 0.95 m according to the ergonomic rules. The *Initial set-up* sub-section allows performing these tasks, requiring the current height of the central conveyor and the status of the fast-picking area. As an example, if the fast-picking area is opened and the height of the conveyor is 1.1 m, inserting these parameters and clicking the SET button, the software architecture automatically reconfigures the system, closing the picking area and lowering the conveyor to a height of 0.95 m. At this moment, a green square appears in the *Control* sub-section to indicate a correct initial setting. This sub-section allows also to manually setting the height of the central roller conveyor by inserting the gap between the current position and the desired position (Δh) or the exact value of the desired height (h).

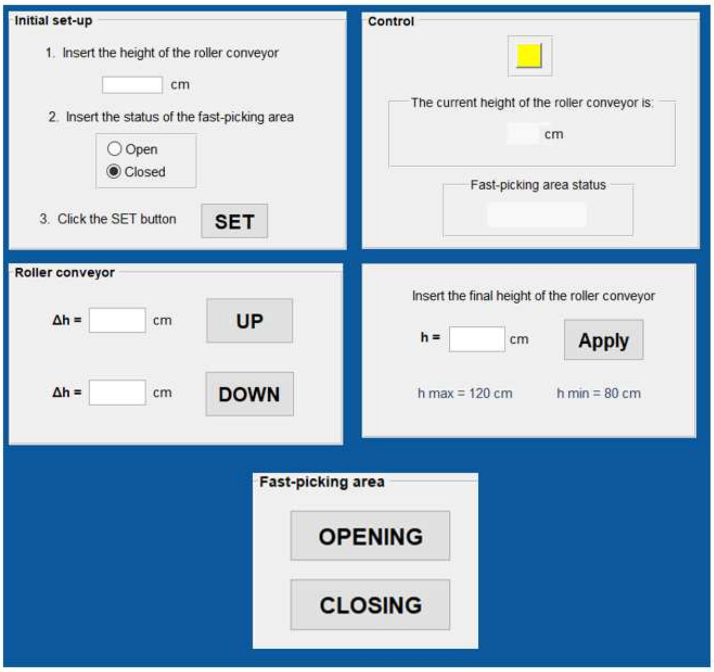


Figure 28: Setting section of the developed GUI

4.4.1.3 *Product and New products windows*

The *Products* and *New Product* sections are the most relevant ones characterizing the proposed GUI. In particular, the former (Figure 29, left) allows the execution of a list of SASAS movements corresponding to the assembly of a specific product realized by the industrial company, according to its work cycle. As example, if the operator needs to assemble the product "Chiller", clicking on *Push to execute product tasks* button at the end of the execution of each assembly operation, the SASAS automatically reconfigures itself in terms of opening/closing of the fast-picking area and vertical moving of the central roller conveyor according to the need of the next assembly operation.

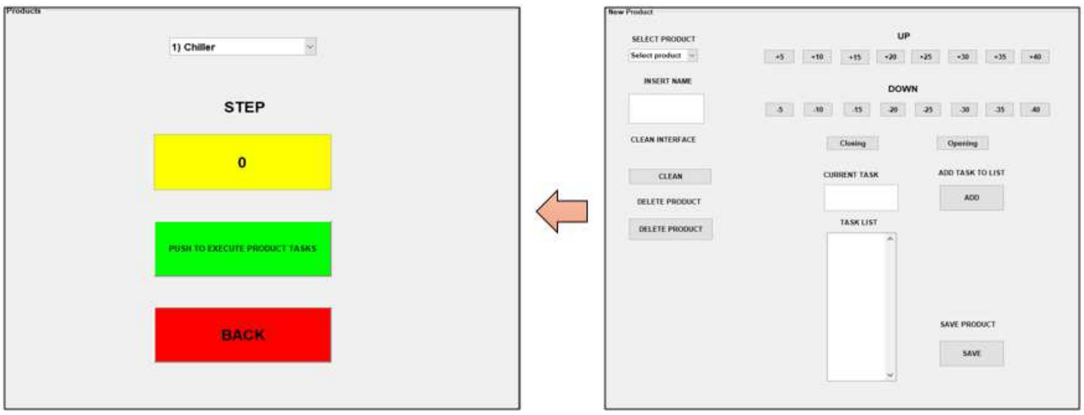
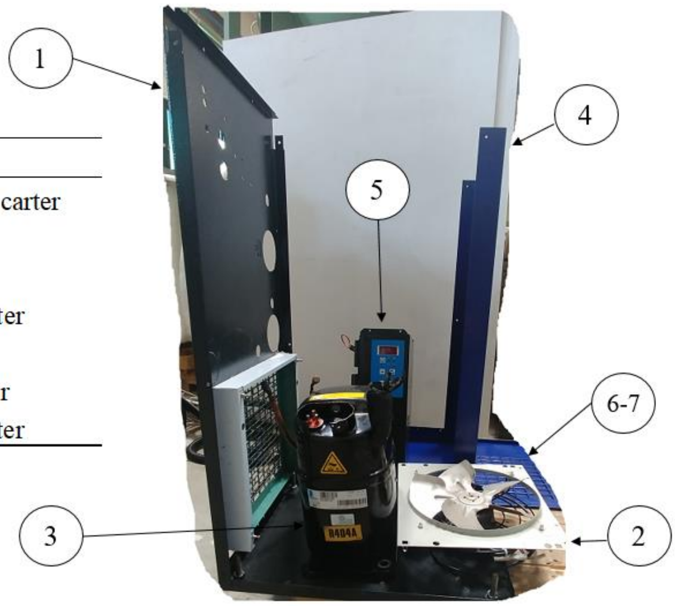


Figure 29: Product and New products sections of the developed GUI

The New product section (Figure 29, right) confers higher levels of flexibility to the use of the self-adaptive system. This window allows in any moment to insert new products work cycles, store them, and make them available in the pop-up menu of the *Products* section. This feature is relevant because in the emerging context of Industry 4.0, which represents a way from mass customization to mass personalization production, customers ask for an increasing number of customized products which differ in shape, colour and size. In this scenario, industrial companies have to cope with the increased product variety rapidly and efficiently (Galizia et al., 2019). The *New product* section efficiently supports the human operators in product variety management allowing them to quickly insert new products work cycles selecting the appropriate SASAS movements from an available library.

4.4.2 Prototype experimental productivity field-test

The preliminary lab field-test aims at testing the prototype working conditions within a realistic full-scale environment by using the developed GUI. The focus is on the assembly process of the industrial chiller in Figure 30, further including a simplified bill of materials. The product dimensions are of about 370x500x764(h) mm, while the components to assemble are to place both on the bottom and on the top of the carter structure.



Id.	Components
1	Bottom cover carter
2	Cooling fan
3	Compressor
4	Top cover carter
5	CPU
6	Left side carter
7	Right side carter

Figure 30: Industrial chiller used for the lab experimental field-test

The developed analysis is multi-scenario and comparative among the three different assembly configurations listed in the following.

- *Configuration #1*: standard assembly + line stocking component feeding;
- *Configuration #2*: SASAS prototype use + line stocking component feeding;
- *Configuration #3*: SASAS prototype use + kitting component feeding.

In *Configuration #1*, the prototype is used as a fix workstation with no adaptation to the part and operator features. The main roller conveyor is set to a height of 0.95 m and the two modules that characterize the fast-picking area are as in Figure 1. The components and the support tools, e.g. screws, screwdrivers, etc., are stored in a shelf unit located behind the assembly workstation, at a distance of 2 m. In *Configuration #2* the SASAS reconfigurability features are used. In such a configuration, the system real-time changes its hardware position following the working cycle of the product. In this scenario, the components are stored in the shelf unit located behind the workstation, while the support tools, e.g. screws, screwdrivers, etc., are stored in the fast-picking area of the assembly workstation. Finally, in *Configuration #3*, the prototype is as in *Configuration #2* but the kitting feeding policy is adopted (Hua and Johnson, 2010). Components are fed in a kit located on the left lateral roller conveyor, while the support tools are located in the fast-picking area. Figure 31 shows changes while switching from line stocking to the kitting feeding policy.

Figure 31: Assembly system configuration with line stocking (left) and kitting (right)

The multi-scenario analysis focuses on the assembly process monitoring the cycle time T_c, i.e. the duration of the assembly tasks, to get the system productivity $Q = \frac{1}{T_c}$. Assembly time values are collected through multiple lab field-tests. For each configuration, according to statistics, a lower bound to the number of tests, n, to get reliable data is by applying Equation (1) (Kenny, 1986):

$$n = \left(\frac{z}{h} \cdot \frac{\sigma}{t}\right)^2 \qquad (1)$$

where:

n	minimum number of tests
t	mean assembly time [s]
σ	standard deviation of the assembly time [s]
z	confidence interval [%]
h	margin of error [%]

Equation (1) correlates the minimum number of tests to their duration, supposed to be normally distributed, i.e. $N(t, \sigma)$, the expected confidence interval and the accepted margin of error. During the experimental field-tests, an incremental approach is used comparing the number of tests to the current value of n until in all configurations a good confidence level is reached. Results are collected in Table 20 after a sequence of ten tests per each configuration. Because of n is equal to 5.67 in *Configuration #1*, 8.50 in *Configuration #2* and 8.38 in *Configuration #3*, a statistic significance is guaranteed.

Table 20: Field-test results for the three configurations, cycle time [s/pc]

Test Id.	Cycle time in Configuration #1	Cycle time in Configuration #2	Cycle time in Configuration #3
1	124	100	74
2	117	96	75
3	119	91	67
4	130	95	70
5	126	85	71
6	112	83	80
7	119	88	75
8	115	92	71
9	121	81	73
10	115	85	62
Mean assembly time (t)	119.8	89.6	71.8
Standard deviation (σ)	5.27	5.9	4.67
Confidence interval at 99% (z)	2.58	2.58	2.58
Margin of error (h)	0.02	0.02	0.02
Minimum sample size (n)	5.67	8.5	8.38

Starting from the obtained field-results, the system productivity for all configurations follows as in Table 21.

Table 21: Average productivity for the three configurations [pcs/h]

	Average productivity	Increment
Configuration #1	30.0	-
Configuration #2	40.2	34.0%
Configuration #3	51.1	70.3%

Results show the impact of the SASAS adoption both itself and when combined to an advanced component feeding policy, i.e. kitting policy. Compared to *Configuration #1*, the cycle time decreases by 25.2% in *Configuration #2* and by 40% in *Configuration #3*, while the productivity increases by 34.0% in *Configuration #2* and by 70.3% in *Configuration #3*.

Behind these performance improvements, a relevant element is due to savings in the picking time and operator movements within the working environment. To quantify such savings, a space analysis is done using a Motion Capture (MOCAP) system collecting dynamic data on the operator positions during assembling. Results are post-processed getting *spaghetti charts* tracing the travelled distance during the task execution. Figure 32 exemplifies the charts for *Configuration #1* and *Configuration #2* while tracking the operator body.

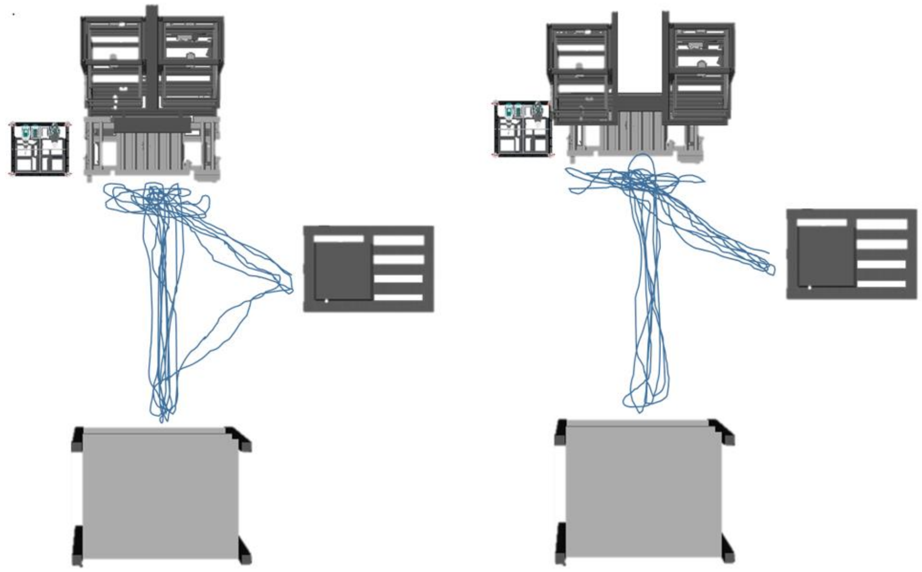


Figure 32: Spaghetti chart of operator body movements for Configuration #1 (left) and Configuration #2 (right), top view

The overall travelled distance during the assembly process is close to 30 m for *Configuration #1* and 20.5 m for *Configuration #2* with a saving of about 31.7% due to low accesses to the storage locations behind the operator. Figure 33 compares the right-hand movements between *Configuration #2* and *Configuration #3*.

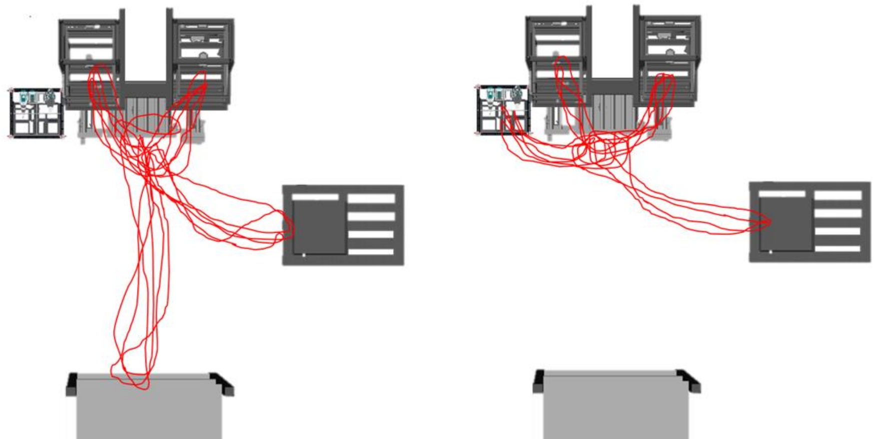


Figure 33: Spaghetti chart of operator right-hand movements for Configuration #2 (left) and Configuration #3 (right), top view

The overall distance is equal to 27.6 m for *Configuration #2* and 15.6 m for *Configuration #3* with a reduction of 43.3% highlighting the strong impact of the kitting feeding policy on the operator movements allowing the full cut off of the storage area in the back of the operator position.

4.5 AUTOMATIC REAL-TIME SYSTEM RECONFIGURATION

The system in Figure 34 is the SASAS equipped with a 3-D sensing device for real-time adjustment. The system acquires the anthropometric measurements by means of such device and arranges the mobile elements of the assembly workstation accordingly. The aim is to adapt the workstation features to the body dimensions of the operator, reducing the risks of biomechanical overload and awkward postures, and improving the workers' health and safety.

Figure 34: SASAS equipped with Microsoft Kinect™

The 3-D sensing device used in this study is a Microsoft Kinect™™ and it is placed on the side of the SASAS. The device is equipped with an RGB camera, an infrared projector and a monochromatic CMOS sensor. Thanks to this equipment, the Kinect™ is able to recognize and trace human movements in 3-D space. The device includes a structured light 3-D scanner which uses projected light patterns and a camera system to calculate the depth of the objects in the space.

4.5.1 Test cases

Two test studies have been developed to test the reliability of the anthropometric measurements acquired with the 3-D sensing device. Test 1 aimed to determine the optimal position of the 3-D sensing device testing different locations of the camera. Test 2 investigated a sample of 10 individuals, with one scan for each individual. The two tests were carried out in the Laboratory of Industrial Engineering at the University of Bologna (Italy) where the SASAS is located. The prototype, as in Figure 34, has limited dimensions and the laboratory environment is characterized by a light brightness, comparable with that of a traditional industrial context, allowing to overcome the main limitations of the Kinect™ cameras.

In the first test, the height and the inclination of the camera have been modified. Specifically, four different height of the camera have been tested and each height is associated to a different camera inclination, for a total of 12 sub-tests (Table 22). The height of the camera varied from 1.50 to 1.70 m, while the inclination ranged from -8° to 15°. Such values are selected since they allow an efficient and accurate human body tracking. The distance of the 3-D sensing device from the assembly worker was fixed at 3 m. The investigated anthropometric measurements were: elbow height, eyes height, elbow-hand grip length, arm length, shoulders height (ISO, 2017). The results of the Test 1 are in the following Table 22. Observed values are the measurements tracked with the 3-D sensing device. Effective values refer to the real body dimensions and they are measured by using an anthropometer tool. Observed and effective measurements have been compared. Delta represents the absolute difference between the two measurements. The lower the value of Delta, the higher the precision of the measurement.

Table 22: Results of Test 1

Sub-test number		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Camera height (m)		1.70	1.70	1.70	1.80	1.80	1.80	1.60	1.60	1.60	1.50	1.50	1.50
Inclination (°)		0°	-20°	-15°	0°	-20°	-15°	0°	-15°	15°	0°	-8°	8°
Elbow height (m)	Observed	1.03	1.29	1.26	0.95	1.23	1.29	1.18	1.19	0.83	1.04	0.87	1.26
	Effective	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
	Delta	0.12	0.14	0.11	0.2	0.08	0.14	0.03	0.04	0.32	0.11	0.28	0.11
Eyes height (m)	Observed	1.5	1.75	1.77	1.42	1.75	1.76	1.68	1.72	1.37	1.57	1.34	1.78
	Effective	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77
	Delta	0.27	0.02	0	0.35	0.02	0.01	0.09	0.05	0.4	0.2	0.43	0.01
	Observed	0.24	0.27	0.30	0.3	0.34	0.29	0.31	0.34	0.29	0.27	0.29	0.35

Elbow-hand grip length (m)	Effective	0.30	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Delta	0.06	0.08	0.05	0.05	0.01	0.06	0.04	0.01	0.06	0.08	0.06	0
Arm length (m)	Observed	0.28	0.28	0.32	0.28	0.34	0.29	0.31	0.34	0.34	0.32	0.27	0.33
	Effective	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
	Delta	0.12	0.12	0.08	0.12	0.06	0.11	0.09	0.06	0.06	0.08	0.13	0.07
Shoulders height (m)	Observed	0.43	0.44	0.44	0.43	0.44	0.43	0.44	0.45	0.44	0.44	0.43	0.44
	Effective	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
	Delta	0.02	0.01	0.01	0.02	0.01	0.02	0.01	0.00	0.01	0.01	0.02	0.01
Average error		0.12	0.07	0.05	0.15	0.04	0.07	0.05	0.03	0.17	0.10	0.18	0.04

The results of Test 1 show that positioning the camera at a height of 1.6 m with an inclination of -15 ° with respect to the horizontal ensures higher precision (Sub-test 8).

The body dimensions of 10 individuals were measured in Test 2. The experimental setup was similar to Test 1, i.e. the distance of the 3-D sensing device from the assembly worker was fixed at 3 m and the anthropometer is used to measure the effective values of the body parts. In particular, the investigated anthropometric measurements were: elbow height, eyes height, elbow-hand grip length, arm length, shoulders height. One scan was performed for each assembly worker. Specifically, the inclination and the height of the camera in Test 2 were set as in Sub-test 8 of Test 1. The results of Test 2 are in Table 23.

Table 23: Results of Test 2

Sub-test number		1	2	3	4	5	6	7	8	9	10	Average [m]	Average [%]
Sex (M=male, F=Female)		M	M	M	F	M	M	F	M	F	M		
Height (m)		1.87	1.85	1.73	1.57	1.70	1.93	1.59	1.80	1.64	1.79		
Elbow height (m)	Observed	1.31	1.29	1.09	1.14	1.17	1.33	1.1	1.24	1.05	1.24		
	Effective	1.3	1.28	1.07	1.04	1.04	1.19	0.98	1.14	1	1.09		
	Delta	0.01	0.01	0.02	0.1	0.13	0.14	0.12	0.1	0.05	0.15	0.083	8
Eyes height (m)	Observed	1.76	1.78	1.68	1.59	1.62	1.85	1.53	1.71	1.55	1.68		
	Effective	1.77	1.75	1.63	1.49	1.6	1.83	1.51	1.7	1.56	1.69		
	Delta	0.01	0.03	0.05	0.1	0.02	0.02	0.02	0.01	0.01	0.01	0.028	2
Elbow-hand grip length (m)	Observed	0.32	0.37	0.33	0.25	0.34	0.39	0.28	0.37	0.3	0.35		
	Effective	0.3	0.37	0.33	0.29	0.32	0.36	0.3	0.37	0.33	0.37		

	Delta	0.02	0	0	0.04	0.02	0.03	0.02	0	0.03	0.02	0.018	6
Arm length (m)	Observed	0.39	0.3	0.31	0.28	0.35	0.31	0.26	0.37	0.3	0.39		
	Effective	0.4	0.35	0.34	0.3	0.35	0.36	0.29	0.38	0.34	0.38		
	Delta	0.01	0.05	0.03	0.02	0	0.05	0.03	0.01	0.04	0.01	0.025	8
Shoulders height (m)	Observed	0.44	0.42	0.46	0.42	0.44	0.46	0.4	0.46	0.42	0.45		
	Effective	0.45	0.46	0.47	0.41	0.45	0.49	0.42	0.47	0.43	0.46		
	Delta	0.01	0.04	0.01	0.01	0.01	0.03	0.02	0.01	0.01	0.01	0.016	4

The percentage average errors in Table 23 range between 2% and 8%. Such values are acceptable for the purposes of this study. Once determined the optimal position of the 3D-sensing device and tested the effective and accurate tracking of human body parts, the next step was to allow a real-time reconfiguration of the SASAS by including ergonomic aspects in the assembly system logic control.

4.5.2 Including ergonomics in the logic control of SASAS

To allow a real-time reconfiguration of the SASAS prototype according to the anthropometric measurements of the human operators, an integration between the phases of logic control programming and the skeleton tracking is mandatory. To do this, MATLAB software is used as common programming environment, by using the Motion Logic Programming Interface (MLPI) libraries for the SASAS logic control programming and the Image Acquisition Toolbox (IAT) for the skeleton tracking. IAT is a computer vision-based tool that provides functions and blocks that enable to connect industrial and scientific cameras, i.e. 3D depth cameras, machine vision cameras, and frame grabbers, to MATLAB and Simulink. The device used in this study is a Microsoft Kinect™. It is equipped with two main sensors: one color sensor to acquire RGB images and one depth sensor to acquire skeletal data.

The acquisition of the anthropometric measurements consists in detecting the body dimensions of the operator in front of the assembly workstation. After a short initial setup for the necessary input configurations, the skeleton tracking function is launched. Specifically, the skeleton is a set of points (joints) positioned in relevant areas of the body. The relative distances between the points of the skeleton are calculated and the anthropometric measurements of interest are extracted. The detected anthropometric measurements are transmitted to the anthropometric module of the SASAS logic control, which proposes to the actuators the positions that the workstation has to assume. The outputs of the anthropometric module are the inputs for the self-adaption of the SASAS (Figure 35).

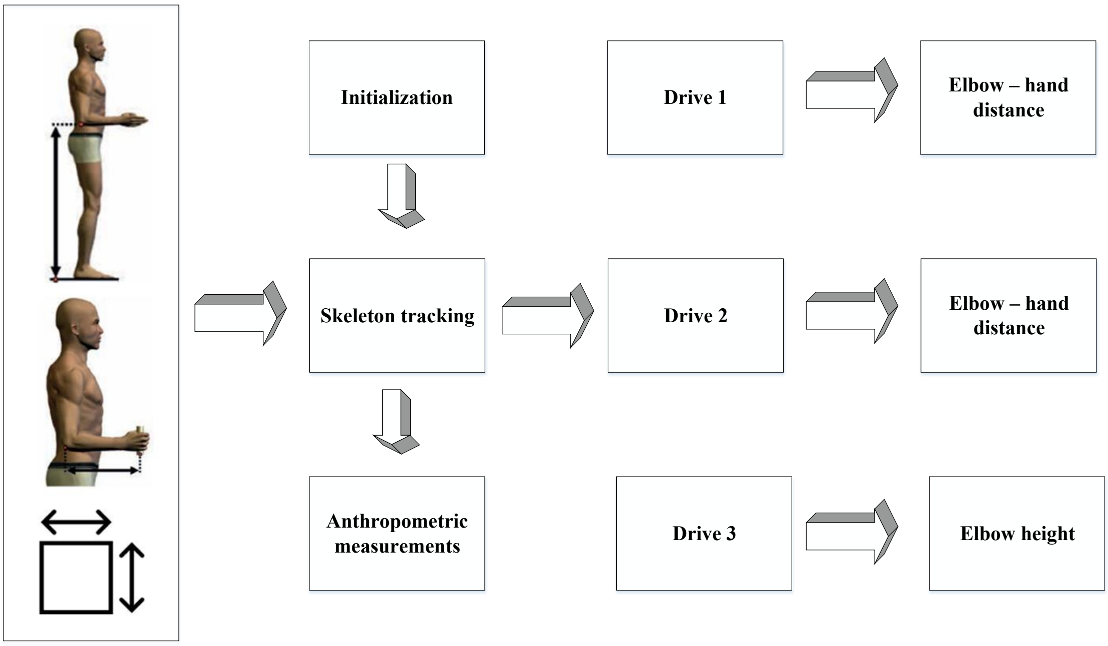


Figure 35: Anthropometric module composition and purposes

The programming code for the anthropometric module of the SASAS consists of three sections: Drive 1, Drive 2 and Drive 3. The first section determines the frontal extension of the modules (Drive 1). The ergonomic principle for the design of ergonomic workplace suggests to set the work area and working devices within the so called "golden zone". The golden zone in ergonomics refers to the area between the mid-thigh and mid-chest (Botti et al., 2017). Given the characteristics of SASAS in Figure 34, the aim is to set the frontal extension of the module allowing the operator to take the assembly parts accordingly to the distance between the elbow and the hand. The extension of the module is inversely proportional to the arm length. Moreover, the closer the modules to the workpiece, the less is the distance that the worker's hand has to cover. As results, a shorter distance to pick the assembly parts leads to reduced number of movements, improved ergonomic conditions, shorter time to assemble the components and higher productivity.

Drive 2 sets the lateral extension of the two modules while Drive 3 computes the position of the third axis, which controls the height of the work surface. The ISO 14738: 2002 suggests to set the height of the work surface accordingly to the type of activity to perform. In case of precision work, the working surface should be higher than the elbow height; in case of low-precision work, e.g. the assembly of the centrifugal electric pump described in the following, the height of the work surface should be equal to or lower than the elbow height. This allows the operator to work at a 90 degree angle between the arm and the forearm. To validate the automatic SASAS reconfiguration through Microsoft Kinect™, the assembly of a centrifugal electric pump is simulated and presented in the following.

4.5.3 The assembly of a centrifugal electric pump

This section introduces the characteristics of the investigated case study and the ergonomic risk assessment for an assembly process performed at a traditional assembly workstation with a fixed layout in the first stage (*Configuration #1*) and at the SASAS prototype equipped with Microsoft Kinect™ in the second stage (*Configuration #2*) for comparison. A male operator (height 1.80 m, weight 85 kg, age 30) simulated the assembly process of an horizontal multistage centrifugal electric pump. Figure 36 and Table 24 show the sketch and the bill of materials for the reference pump.

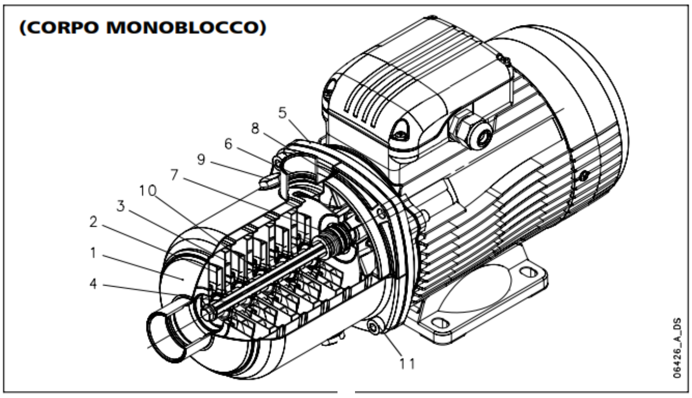


Figure 36: Parts of the multistage horizontal centrifugal electric pump

Table 24: Bill of materials for the horizontal multistage centrifugal electric pump

Reference	Parts
1	Pump crankcase
2	Rotor
3	Diffuser
4	Shaft
5	Adapter
6	Seal housing disc
7	Mechanical seal
8	Elastomers
9	Fill / drain plugs
10	Wear ring
11	Bolts and screws

This study focuses on the assembly of the pump components characterized by high weight and size i.e. pump crankcase, rotor and seal housing disc. The remaining components are small metal parts and their assembly is not relevant for the purposes of this study. Specifically, the reference assembly tasks consist in placing the rotor in the pump crankcase and positioning the seal housing disc on it. Figure 37 shows the crankcase, the rotor and the seal housing disc of the multistage centrifugal electric pump.

Figure 37: Parts of the horizontal multistage centrifugal electric pump. From the left: seal housing disk, pump rotor, pump crankcase

The assembly worker performed the technical actions in Table 25 to assemble one pump. Table 25 shows the technical actions of each arm and the time required in seconds.

Table 25: Technical actions performed with each arm to assemble the parts in Figure 37

Technical actions performed with the left arm	*Time [s]*	*Technical actions performed with the right arm*	*Time [s]*
Move the work table towards the operator	2		-
Take the rotor	3		-
Place the rotor	2	Place the rotor	3
		Take the seal housing disk	2
Positioning	2	Positioning	2
Fix the components	1	Fix the components	1

	-	Move the work table to the right	2

The work piece arrives from the previous assembly workstation on a table. At this stage, the crankcase is fixed on the workpiece. The assembly worker moves the object with the left hand to the main roller conveyor and takes the rotor from the box on the module. Then, the worker places this component with both hands inside the crankcase. With the right hand, the worker takes the seal housing disk and places it with both hands on the crankcase. Some pressure is required to fix the two components correctly. Finally, the right hand pushes the work table on the right, moving the workpiece towards that direction. The cycle time required to perform the introduced assembly task is 17 s. The pace of the operation depends on the takt time imposed by the production strategy. The ergonomic risk due to repetitive movements of the upper limbs has been assessed, considering the case study of an assembly worker who is required to perform the described assembly operation during a 8-hour shift. 30-minute break are included and the net duration of the repetitive task is 450 min. The production volume considered for the ergonomic risk assessment is 1570 pieces per worker and work-shift. Finally, the simulation considered the presence of seven hours during the work-shift with proper recovery, as required by the ISO 11228-3:2007 (ISO, 2007).

In *Configuration #1*, the main roller conveyor was set to a height of 0.95 m and the two modules that characterize the picking area were positioned as in Figure 34. The following Table 26 shows the investigated parameters for the ergonomic risk assessment of the assembly operation in *Configuration #1* by using OCcupational Repetitive Action (OCRA) method for the evaluation of risk factors in relation to repetitive movements with the upper limbs (Colombini and Occhipinti, 1997). The OCRA index investigates the ratio between the number of actual technical actions, necessary to perform the task, and the number of reference technical actions, recommended for ensuring an acceptable risk.

Table 26: List of the OCRA parameters and indices for the assembly operation in the fixed workstation (Configuration #1)

Parameter	*Left arm*	*Right arm*
Force multiplier	0.72	0.80
Posture multiplier	0.70	0.70
Additional multiplier	0.85	0.85
Repetitiveness multiplier	0.70	0.70
Cycle time [s]	17.6	17.6
Frequency (technical actions per minute)	17	17
Duration multiplier	1.1	1.1
Actual technical actions	7000	7000

Recommended technical actions	4057	4506
OCRA Index	1.7	1.6

The OCRA indices for both the right and the left arm reveal acceptable exposure to the risk of repetitive movements, i.e. the threshold limit value for the presence of high risk is 2.1.

In *Configuration #2*, the assembly process was performed at the SASAS equipped with Microsoft Kinect™™. In such a configuration, the control program real-time sets the main roller conveyor height and the position of the two modules accordingly to the operator's anthropometric measurements. A second ergonomic risk assessment was performed. The results are in the following sub-section 4.5.4.

4.5.4 Results and discussion

The assembly operation presented in Section 4.5.3 was performed at the SASAS with the 3-D sensing device, i.e. Microsoft Kinect™. The control program was activated and the 3-D sensing device retrieved the anthropometric measurements of the operator at the workstation, i.e. the inputs of the control program for the smart workstation are the anthropometric measurements of the operator. A second ergonomic risk assessment with the OCRA method was performed to investigate the impact of automation and 3-D sensing on the risk of repetitive movements. Table 27 summarizes the OCRA parameters and the results of the ergonomic risk assessment.

Table 27: List of the OCRA parameters and indices for the assembly operation at the SASAS (Configuration #2)

Parameter	*Left*	*Right*
Force multiplier	0.72	0.80
Posture multiplier	0.70	1.00
Additional multiplier	0.85	0.85
Repetitiveness multiplier	0.70	0.70
Cycle time [s]	17.6	17.6
Frequency (technical actions per minute)	17	17
Duration multiplier	1.1	1.1
Actual technical actions	7000	7000
Recommended technical actions	4057	6437
OCRA Index	1.7	1.1

The OCRA index for the right limb improved significantly from 1.6 (Table 26) to 1.1 (Table 27). The OCRA index for the left arm is constant and equal to 1.7.

The operator revealed that the assembly tasks at the smart assembly station required less effort and muscular fatigue, compared with the fixed workstation. Specifically, the worker stated that the effort required to reach the assembly parts was reduced in the smart workstation. In addition, such workstation improved the comfort of back, neck and shoulders, thanks to the optimal height of the work surface.

Figures 38, 39 and 40 show three assembly tasks performed at the fixed workstation (left) and at the SASAS (right). In Figure 38, the operator takes the rotor from the module. Figure 39 shows the assembly of the rotor in the crankcase, while Figure 40 shows the positioning of the seal housing disc.

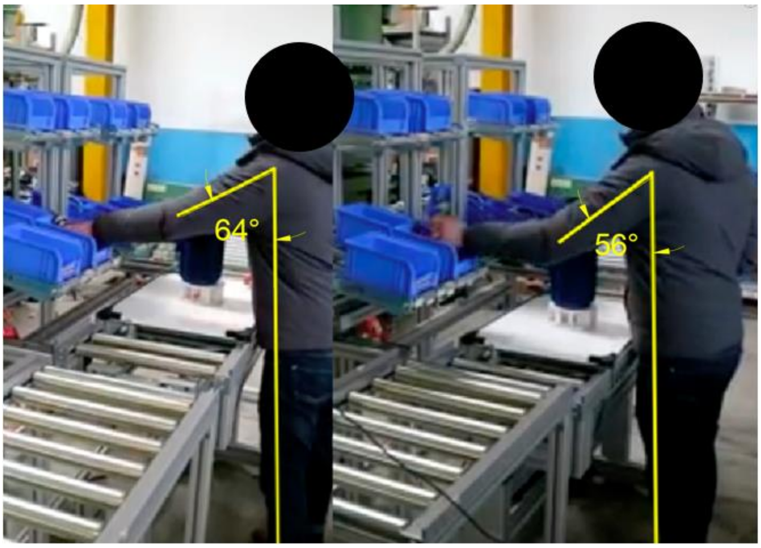


Figure 38: Picking of the rotor from the module (left: fixed workstation; right: SASAS)

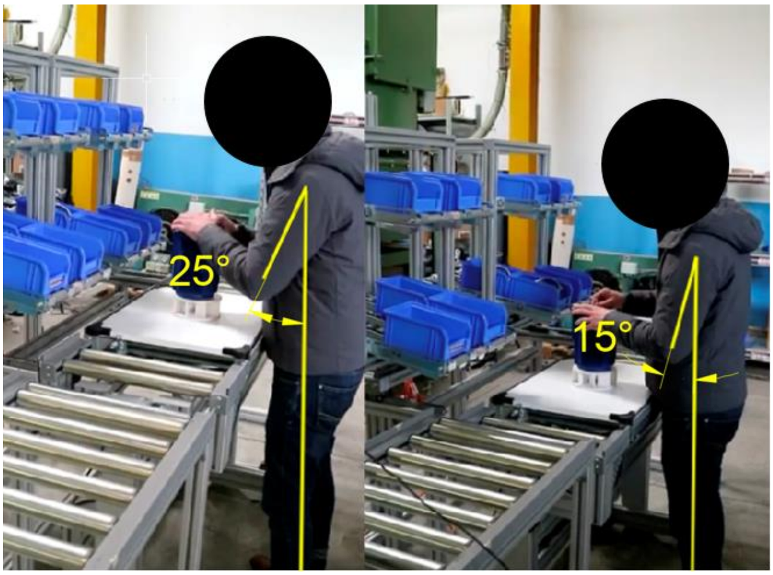


Figure 39: Assembly of the seal housing disk (left: fixed workstation; right: SASAS)

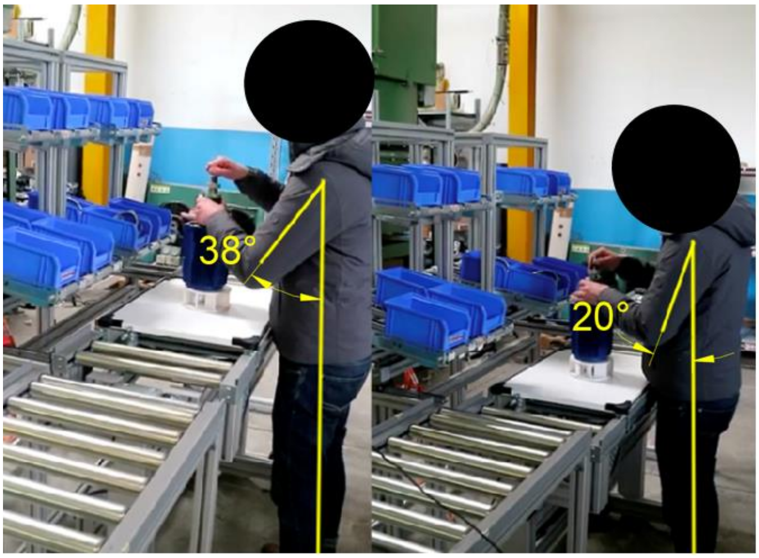


Figure 40: Insertion of the rotor into the crankcase (left: fixed workstation; right: SASAS)

Figures from 38 to 40 show also the impact of the SASAS on the shoulder posture. Specifically, the shoulder flexion reduces with the adaption of the workstation to the operator's body dimensions.

Table 28: Variation of the shoulder flexion angle using the fixed workstation and the SASAS

Assembly task	*Fixed workstation [°]*	*SASAS [°]*	*Reduction [°]*	*Percentage reduction [%]*
Picking of the rotor from the module	64°	56°	8°	13%
Assembly of the seal housing disk	25°	15°	10°	40%
Insertion of the rotor into the crankcase	38°	20°	18°	47%

Results in Table 28 confirm that the SASAS allows a significant reduction of the shoulder flexion angle. The maximum reduction is obtained when the operator inserts the rotor into the crankcase, i.e. the shoulder flexion angle in the SASAS is reduced by 47%. The ergonomic risk assessment confirmed the improvement of the ergonomic conditions and the ergonomic benefits of such system. Furthermore, the proposed approach improves the traditional approaches for the design of assembly workstations.

4.6 INDUSTRIAL CASE STUDY

Once demonstrated the benefits coming from the adoption of SASAS in terms of productivity and ergonomics, it is set up in a real Italian industrial company assembling industrial refrigerators for validation. The market mix is wide so that manual assembly is still used. The assembly line is made of four stations equipped with components, tools and auxiliary materials to perform the assembly tasks. After the setup and training of the operators to make them confident with the new assembly system, the same multi-scenario analysis developed during the lab experimental field-test is done collecting results on the overall productivity increase. Figure 41 shows the initial conditions with no use of the new solution. In particular, all components and support tools are stored in a shelf unit behind the assembly workstation, i.e. line stocking strategy is implemented.

Figure 41: Industrial case study, Configuration #1, base scenario

Figure 42 presents the new configuration after the SASAS adoption. Support tools are stored in the fast-picking area of the assembly workstation while, according to the kitting strategy, product components are fed in a kit located on the left lateral roller conveyor.

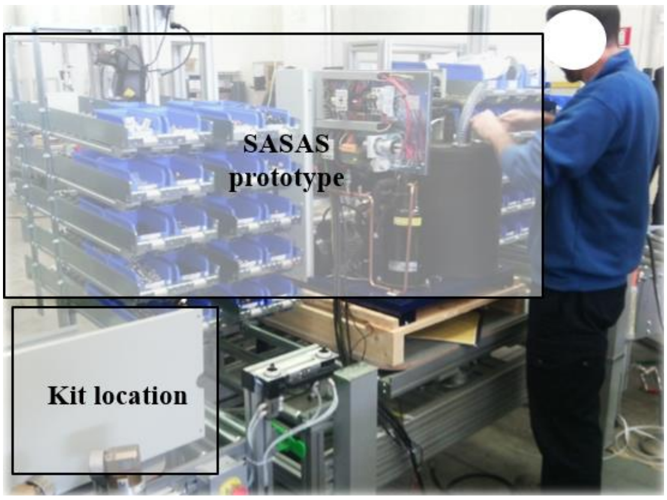


Figure 42: Industrial case study, Configuration #3 adopting the developed prototype

The comparative analysis is performed collecting data for operators with different skills and over a period of two weeks. Aggregate results show, on average, a reduction of the cycle time up to 38%, a productivity increase close to 66% and a reduction of the shoulder flexion angle, i.e. ergonomic perspective, close to 34%, confirming the benefits of the SASAS introduction compared to the previous traditional assembly conditions adopted by the company. Positive feedbacks came, also, from the line operators stating better working conditions and an increased quality of their daily activities.

4.7 CONCLUDING REMARKS

This chapter presents the design, engineering and testing of an innovative prototypal reconfigurable assembly system, called Self-Adaptive Smart Assembly System (SASAS). The prototype includes a fast-picking area located in front of the operator working area, to store components, equipped with two motion axes to optimize its relative position. A third motion axis allows the reconfiguration of the working plane to ease the operator movements. The main element of innovation of the system is the ability to reconfigure itself according to the product working cycle and the operator features allowing a potential reduction of the movements during the picking and assembly phases for both small and medium size products, with a volume up to $1.5m^3$. A multi-scenario lab field-test proves the benefits of the proposed prototype in terms of flexibility, productivity, and ergonomics assessing the full-scale assembly of an industrial chiller and of a centrifugal electric pump, further adopting traditional, i.e. line stocking, and advanced, i.e. kitting, component feeding policies. Compared to the base case, i.e. traditional assembly system, the SASAS prototype allows a significant reduction of the assembly cycle time and of the operator movements as well as an improvements of the ergonomic work conditions in terms of shoulder flexion angle reduction during the assembly process with a consequent improvement of the productivity (up to 70.3% in the lab-tests). Finally, an application to industry is presented to validate the system in a relevant industrial scenario. Evidences confirm the upgrades in terms of flexibility, productivity and ergonomics making the proposed system of potential interest and immediate applicability within industry. Future developments of this study include further industrial applications in other relevant sectors.

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Appendix C

High-level pseudocode of the main control instructions to real-time manage the workplace (WP) and the storage modules (SM) of the SASAS. Calls to IndraWorks standard functions are underlined.

```
main begin

# variable declaration
var WP_pointer, SM_pointer as axis_pointer;
var WP_position, WP_upper_limit, WP_lower_limit as real;
var SM_position as boolean;
var phase_index, num_phases as integer;
var workcycle[1..num_phases] as cluster of {WP_target,SM_target};

# workcycle data loading
read product input from external file: save data into {num_phases, workcycle};

# SASAS axis initialization
WP_pointer:=get_motion_axis("physical_path_to_workplace_driver");
WP_position:=95;
WP_upper_limit:=120;
WP_lower_limit:=75;
f_workplace(WP_pointer,f_position(WP_pointer),WP_position);
SM_pointer:=get_motion_axis("physical_path_to_storage_module_driver");
SM_position:=false;
f_storage_module(SM_pointer,f_position(SM_pointer),SM_position);

# SASAS real-time control and self-adaptation
phase_index:=1;
do
        if (workcycle[phase_index,WP_target]<WP_lower_limit) or
    (workcycle[phase_index,WP_target]>WP_lower_limit)
                then
                        begin
                                send warning to user;
                                wait rebuttal from user;
                                f_workplace(WP_pointer,f_position(WP_pointer),95);
                                WP_position:=95;
                                f_storage_module(SM_pointer,f_position(SM_pointer),false);
                                SM_position:=false;
                                terminate;
                        end
                else
                        begin
                                f_workplace(WP_pointer,f_position(WP_pointer),WP_target);
                                WP_position:=WP_target;
                                f_storage_module(SM_pointer,f_position(SM_pointer),SM_target);
                                SM_position:=SM_target;
                                wait until USER OK;
                                phase_index++;
                        end
while (phase_index <= num_phases);

f_workplace(WP_pointer,f_position(WP_pointer),0);
```

```
WP_position:=95;
f_storage_module(SM_pointer,f_position(SM_pointer),false);
SM_position:=false;

end
```

High-level pseudocode of the two functions called to change the workplace height (f_workplace) and the storage module position (f_storage_module). Calls to IndraWorks standard functions are underlined.

```
function f_workplace(Axis_pointer,Axis_origin,Axis_destination)
begin
if (Axis_origin != Axis_destination)
        then
         begin
                f_motionpower(Axis_pointer,"on");
                if (Axis_origin < Axis_destination)
                then    f_moveabsolute_up(Axis_pointer,Axis_destination - Axis_origin);
                else    f_moveabsolute_down(Axis_pointer,Axis_origin - Axis_destination);
                f_motionpower(Axis_pointer,"off");
         end
end

function f_storage_module(Axis_pointer,Axis_origin,Axis_destination)
begin
if (Axis_origin != Axis_destination)
        then
         begin
                f_motionpower(Axis_pointer,"on");
                if (Axis_destination == 1)
                then    f_moveabsolute_open(Axis_pointer);
                else    f_moveabsolute_close(Axis_pointer);
                f_motionpower(Axis_pointer,"off");
         end
end
```

5 CONCLUSIONS & FURTHER RESEARCH

The main purpose of this dissertation is to propose innovative methods, models and tools aided at introducing the emerging principles of reconfigurability in designing products and advanced production systems to improve the overall performances along the industrial plants. Nowadays, the realization of this goal represents a challenging task for manufacturing. In fact, emerging factors as the increase in the number of product variants, i.e. mass customization, high flexibility, dynamic market demand and flexible batches affect the production strategy to adopt and the design of production systems, driving the transition from traditional manufacturing systems toward the so-called Next Generation Manufacturing Systems (NGMSs).

Based on these statements, the research presented in this dissertation elaborates on three research questions that narrow down the set of potential approaches to the problem of introducing principles of reconfigurability as mean to improving the overall performance of modern production systems, i.e. manufacturing and assembly. Moreover, the research activity is developed according to the research framework in Figure 1, where the research questions are addressed by three main research levers, i.e. (1) design of modular product platforms, (2) design of reconfigurable manufacturing systems and (3) design of reconfigurable assembly systems. Next Figure 43 shows a framework highlighting the main contributions presented in this dissertation.

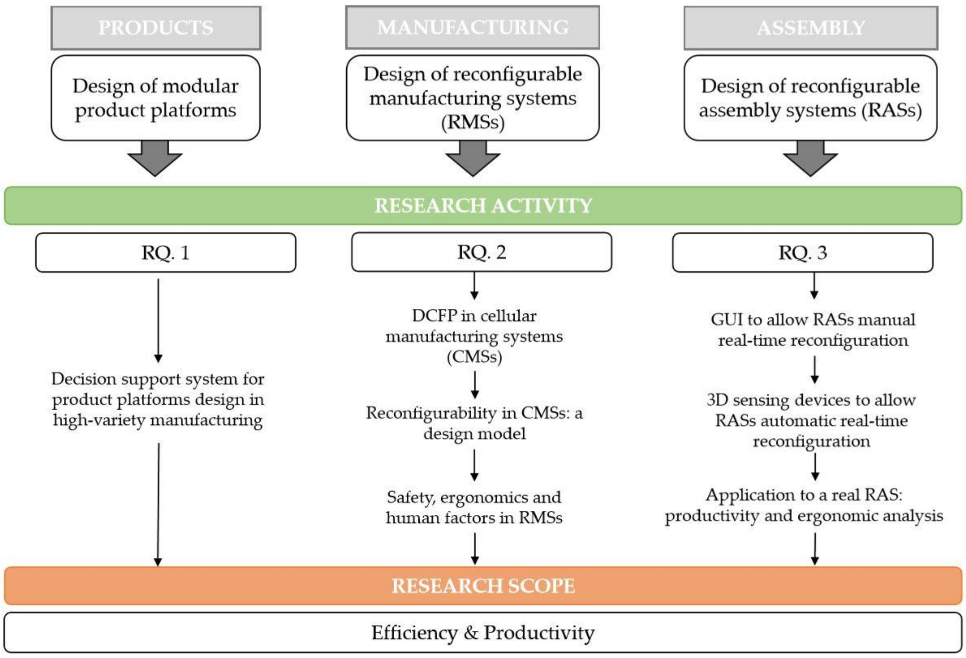

Figure 43: Framework of the main contributions presented in this dissertation

Specifically, following the first research lever, i.e. design of modular product platforms, an integrated decision support system (DSS) for product platforms design and selection in high-variety manufacturing is developed to best manage the trade-off between platforms variety and number of assembly/disassembly tasks needed to customize the platforms into the final product variants. In addition, the developed DSS proposes two new metrics to evaluate the effort to reconfigure the platform into a variant providing conditions that support industrial companies in determining, for each product variant, whether it is better to adopt Delayed Product Differentiation (DPD) or the Assemble to Order (ATO) strategy, and guide them in the selection of effective product platforms. In particular, results show that the developed DSS efficiently supports companies in the design and selection of effective platforms, leading to a reduction of the variety of assembled and stocked products of about 60.5% and to significant production and inventory efficiencies and cost savings. At the same time, the case study company accepted an increase of assembly/disassembly effort required for platforms customization by about 20% and an increase of valves portfolio, which is more than offset by the reduction in inventory cost. Using the assembly/disassembly modular product platforms offer the possibility to produce different products using more than one platform, providing more flexibility in production planning. The introduction of product platforms also helps companies achieving a more flexible response to the introduction of new products mix as well as increased adaptability to changing market demands. Future research deals with the inclusion of the annual demand data of the different product variants to consider its effect on the platforms design.

Following the second research level, i.e. design of reconfigurable manufacturing systems, at first the Dynamic Cell Formation Problem (DCFP) is explored as a reasonable solution able to overcome some weakness of conventional Cellular Manufacturing Systems (CMSs). Afterwards, following the recent shift toward the reconfigurable manufacturing paradigm, the concept of reconfigurability is revised and a design model supporting the optimal design and management of Cellular Reconfigurable Manufacturing Systems (CRMSs) is introduced. In particular, the proposed model supports the design and management of CRMSs in a multi-product and multi-period environment best-balancing the part flows among machines ready to process them and the effort to install the necessary modules on the current machine. The proposed optimal procedure is applied to a relevant case study, made of an instance inspired from the literature, while a multi-scenario analysis widens the analysis assessing the impact of different machine-cell configurations on the system performances. A benchmarking concludes the study comparing the proposed CRMS against a conventional CMS configuration. The analysis shows relevant benefits in terms of reduction of the intercellular travel time (-58.6%) getting a global time saving of about 53.3%. Results prove that reconfigurability is an opportunity for industries to face the dynamics of global markets. In the design and management of these systems, a relevant aspect to consider is the human contribution. In fact, despite their automation level, CRMSs still require actions by human operators, e.g. material handling, WIP load/unload, tool setup, etc, rising safety and ergonomics issues because of the human-machine interaction and cooperation. To managing this aspect, an innovative methodological framework supporting the integration of safety, ergonomics and human factors in these systems is introduced. The main ability of the framework is to identify the main activities to be performed in a reconfigurable environment requiring manual operations and to combine these actions to specific Health & Safety (HS) critical areas, i.e. safety, manual handling tasks, working postures, fatigue and stress. Future research deals with the extension of the proposed CRMS design model to include relevant issues not considered at this stage, e.g. auxiliary module availability, economic assessment, etc., as well as the application to larger industrial instances.

Following the third research level, i.e. design of reconfigurable assembly systems, a conceptual schematic helping to achieving real-time manual and automatic reconfigurations of reconfigurable assembly systems (RASs) is developed. This framework is, then, applied to a real prototypal RAS, called Self-Adaptive Smart Assembly System (SASAS). Its main element of innovation is the real-time reconfiguration according to the product features, the work cycle and the operator features, allowing a reduction of the movements during the picking and assembly phases for both small and medium size products, i.e. gross volume up to $1.5m^3$. Such a real-time reconfiguration can be manually or automatically performed. To reach the first goal, an easy-to-use Graphic User Interface (GUI) is developed and tested to allow the human operators to real-time reconfigure the systems according to their anthropometric measurements, to the product features and product work cycle. In the latter case, 3D sensing devices, i.e. Microsoft Kinect™, are used for SASAS real-time adjustment. In particular, the assembly system acquires the anthropometric measurements of the human operator by means of such devices and arranges its mobile elements accordingly. The aim is to adapt the workstation features to the operator body dimensions, reducing the risks of biomechanical overload and awkward postures, and improving the workers' health and safety. Two lab-experimental campaigns conclude the analysis to compare the performance of the SASAS with that of a traditional assembly system not including elements of reconfigurability and self-adaptability. Results show improvements in productivity, up to 70.3% in the lab-tests, as well as in ergonomic conditions in terms of OCRA index and shoulder flexion angle reduction.

To conclude, this dissertation provides theoretical and practical insights to support real-world industrial companies in facing modern emerging trends, i.e. dynamic market demand, variable batches, and mass customization, through reconfigurability. Effective and use-to-use methods and models are proposed to best design and select product platforms in high-variety industrial contexts and to best design and manage cellular reconfigurable manufacturing systems, applying such methodologies to representative literature and real-world case studies.

In addition to the proposed perspectives, wide opportunities exist for future research in the development of models, tools and methods supporting the introduction of the emerging principles of reconfigurability in the design of product platforms and advanced production systems, i.e. manufacturing and assembly. Moreover, the bibliometric analysis and the schematic map presented in Section 3.2 that allows visualizing the past research trends, could even support researchers in the identification of potential gaps in the literature.

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