UNIVERSIDADE D COIMBRA

Isabela Maganha

Reconfigurability and Design of Manufacturing Systems

Doctoral Thesis in Mechanical Engineering, area of Management and Industrial Robotics, supervised by Professor Cristóvão Silva and submitted to the Department of Mechanical Engineering, Faculty of Sciences and Technology of the University of Coimbra.

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É junto dos ‘bão’ que a gente fica ‘mió’.

João Guimarães Rosa

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Resumo

As empresas precisam de lidar com mudanças cada vez mais frequentes no mercado, como por exemplo, a introdução de novos produtos ou novas tecnologias e grandes variações no volume da procura e no mix de produtos. Os sistemas de produção reconfiguráveis (SPR) assumem grande importância neste contexto. De fato, os SPR assumem um papel relevante para proporcionar alta capacidade de resposta ao mercado, o que é um fator-chave para a competitividade. Os SPR incorporam a reconfigurabilidade, que é essencial para reorganizar os seus componentes face a mudanças ambientais e tecnológicas, de maneira económica. A reconfigurabilidade, por sua vez, é composta por características centrais como modularidade, integrabilidade, customização, escalabilidade, convertibilidade e diagnosticabilidade. No entanto, apesar de sua importância, a realização de SPR na prática, ou seja, a implementação da reconfigurabilidade em sistemas de produção reais, ainda se encontra num estágio inicial. Este estudo pretende contribuir para uma melhor compreensão dos SPR, as suas características centrais e os problemas associados ao seu projeto, a fim de facilitar a implementação futura deste conceito em empresas.

Este trabalho adota uma abordagem multi-metodológica que combina investigação empírica quantitativa e um estudo de caso. Esta tese está estruturada a partir de um contexto genérico para um contexto específico. Esta é composta por três partes principais, cada qual com objetivos específicos. Na primeira parte, um questionário é desenvolvido para investigar o conceito de reconfigurabilidade e até que ponto esta característica está atualmente implementada em indústrias de diferentes setores. O impacto da reconfigurabilidade no desempenho operacional das empresas e a necessidade de reconfigurabilidade em empresas que adotam diferentes estratégias de produção também são discutidos nesta parte da tese. Na segunda parte deste estudo, o problema do projeto de layout no contexto de SPR é analisado. Para tal, uma revisão sistemática da literatura é realizada com o intuito de identificar os principais desafios impostos pelos SPR para o projeto de layout. Além disso, o paradigma da Indústria 4.0 promove novas tecnologias que podem proporcionar às empresas a capacidade de lidar com mudanças abruptas no mercado. A introdução dessas novas tecnologias em sistemas de produção também pode contribuir para alavancar a reconfigurabilidade destes sistemas. Portanto, na terceira parte, são discutidos os impactos da introdução da robótica colaborativa móvel, com o objetivo de alavancar a reconfigurabilidade de linhas de montagem.

As contribuições deste trabalho têm implicações teóricas e práticas. Os contributos da parte empírica quantitativa são úteis para identificar quais são, de fato, as características centrais da reconfigurabilidade, como elas impactam no desempenho operacional dos sistemas de produção e a sua influência sobre sistemas que operam com diferentes estratégias de produção. Os resultados da revisão da literatura apontam várias áreas-chave que podem ser seguidas em pesquisas futuras. As principais contribuições do estudo de caso avançam na identificação das vantagens e desvantagens da introdução de robótica colaborativa móvel nas linhas de montagem. Esse conhecimento é importante para a indústria, pois contribui para a efetiva realização de SPR.

PALAVRAS-CHAVES: Reconfigurabilidade; Sistemas de produção; Inquérito; Algoritmo de lista; Meta-heurística.

Acronyms

ACO	ant colony optimisation
AGV	automated guided vehicles
AHP	analytical hierarchical process
AI	artificial intelligence
AM	analytical modelling
AMOSA	adapted archived multi-objective simulated annealing
ATO	assembly-to-order
AVE	average variance extracted
BOM	bill of materials
CFA	confirmatory factor analysis
CFI	comparative fit index
CMS	cellular manufacturing systems
CNA	citation network analysis
CPPS	cyber physical production systems
CR	composite reliability
CS	case study
DMS	dedicated manufacturing systems
EFA	exploratory factor analysis
ELAA	equipment layout assignment algorithm
ETO	engineer-to-order
ETPN	extended time-placed Petri nets
FMS	flexible manufacturing systems
GA	genetic algorithms

MAS	multi agent system
MH-RMS	movable hybrid reconfigurable manufacturing systems
MILP	mixed integer linear programming
MIP	mixed integer programming
MMA	multi-methodological approach
MTO	make-to-order
MTS	make-to-stock
NSGA-II	non-dominated sorting genetic algorithm-II
PROMETHEE	preference ranking organisation method for enrichment evaluation
PSO	particle swarm optimisation
QE	quantitative empirical
RAS	reconfigurable assembly systems
REM	revised electromagnetism-like mechanism
RFID	radio frequency identification devices
RIM	reconfigurable inspection machines
RLP	reconfigurable layout problem
RMS	reconfigurable manufacturing systems
RMSEA	root mean square error of approximation
RMT	reconfigurable machine tools
RQ	research question
SA	simulated annealing
SD	standard deviation
SPR	sistemas de produção reconfiguráveis
SLNA	systematic literature network analysis
SLR	systematic literature review
SPC	search path count

SRMR standardised root mean square residual

TOPSIS technique for order preference by similarity of ideal solution

TS tabu search

VOS visualisation of similarities

Abstract

Companies must deal with increasingly market changes, such as the introduction of new products, new technologies and large fluctuations on demand volume and product mix. reconfigurable manufacturing systems (RMS) assume a great importance in this context. Indeed, they assume a relevant role in achieving responsiveness, which is a key enabler of competitiveness. RMS have reconfigurability embedded, which is essential to rearrange systems' components to respond to environmental and technological changes in a cost-effective way. Reconfigurability, in turn, is composed by core characteristics such as modularity, integrability, customisation, scalability, convertibility and diagnosability. Nevertheless, despite their importance, the achievement of RMS in practice, *i.e.* the implementation of reconfigurability in actual manufacturing systems, is still in an initial stage. This study is intended to contribute to a better understand of RMS, their core characteristics and design, in order to facilitate the future implementation of this concept in manufacturing companies.

This work adopts a multi-methodological approach (MMA), that combines quantitative empirical research and case study. This thesis is structured from a generic to a specific context. It is composed by three main parts, each with specific objectives. In the first part, a questionnaire survey is developed to investigate the concept of reconfigurability and to what extent this ability is implemented in current manufacturing companies, from different industrial sectors. The impact of reconfigurability in the operational performance of companies and the need for reconfigurability in companies that adopts different business production strategies are also discussed in this part of the thesis. In the second part of this study, the layout design problem in the context of RMS is analysed. To do so, a systematic literature review is conducted intending to identify the main challenges posed by RMS to the layout design problem. In addition to that, the Industry 4.0 paradigm promotes novel technologies that can provide manufacturing companies the ability to cope with abrupt market changes. The introduction of these novel technologies in manufacturing systems may also contribute to leverage their reconfigurability. Therefore, in the third part, the impacts of the introduction of mobile collaborative robotics, aiming at leveraging the reconfigurability of assembly lines, are discussed.

The contributions of this research have theoretical and practical implications. The findings of the quantitative empirical part are useful to identify which are actually the core characteristics of reconfigurability, how they impact on the operational performance of manufacturing systems and their influence on different business production strategies. The outcomes of the literature review highlight many key areas that may be pursued in future research. The main contributions of the case study move towards the identification of the advantages and drawbacks of introducing mobile collaborative robotics on assembly lines. This knowledge is valuable to the manufacturing industry, contributing to the achievement

and design of actual RMS.

KEYWORDS: Reconfigurability; Manufacturing systems; Survey; List algorithm; Meta-heuristic.

List of papers

The following parts of this research have been published, are currently under review or will be submitted soon:

Peer-review International Journals

1. Maganha, I. and Silva, C. (2017). A Theoretical Background for the Reconfigurable Layout Problem. *Procedia Manufacturing*, 11:2025–2033.

2. Maganha, I., Silva, C. and Ferreira, L. M. D. F. (2018). Understanding reconfigurability of manufacturing systems: An empirical analysis. *Journal of Manufacturing Systems*, 48:120–130.

3. Maganha, I., Silva, C. and Ferreira, L. M. D. F. (2018). The layout design in Reconfigurable Manufacturing Systems: a literature review. *International Journal of Advanced Manufacturing Technology* (submitted on October 2018, under the second revision).

4. Maganha I, Silva C, Ferreira LMDF (2018) The impact of reconfigurability on the operational performance of manufacturing systems. *Journal of Manufacturing Technology Management* (submitted on December 2018).

5. Maganha, I., Silva, C. and Ferreira, L. M. D. F. (2019). An analysis of reconfigurability in different business production strategies. *IFAC PapersOnline* (submitted on January 2019).

6. Maganha, I., Silva, C., Klement, N., Beauville, A., Durville, L. and Moniz, S. (2019). Hybrid optimisation approach for assignment and sequencing decision-making in reconfigurable assembly lines. *IFAC PapersOnline* (submitted on January 2019).

7. Maganha, I., Silva, C. and Moniz, S. (2019) Leveraging the reconfigurability of assembly lines through mobile collaborative robots (in preparation).

International Conferences

8. Maganha, I., Kroef, M., Silva, C. and Klement, N. (2018). A hybrid methodology for jobs scheduling on a reconfigurable assembly line, in *XIX Congresso da Associação Portuguesa de Investigação Operacional*, September/2018, Aveiro, Portugal.

9. Maganha, I., Silva, C. and Ferreira L. M. D. F. (2018). Reconfigurability and manufacturing systems operational performance: an exploratory analysis, in *24th International Joint Conference on Industrial Engineering and Operations Management*, July/2018, Lisbon, Portugal.

Technical National Journals

10. Maganha, I. and Silva, C. (2017). Um modelo de apoio à decisão para o problema de layouts reconfiguráveis, *Boletim APDIO*, 56:12-14.

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Part I Introduction

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Chapter 1 Introduction

1.1 Background

Due to the dynamic nature of today's markets, driven by aggressive economic competition on a global scale, companies need to deal with changes in parts of existing products, government regulations, process technology and large fluctuations in demand volume and product mix, which occur with increasing pace. These changes are key factors that require the launch of products with a short life cycle and a high degree of customisation. Thereby, companies face the challenge of designing manufacturing systems that not only produce high-quality products at low costs, but also have high responsiveness to market changes and customer needs (Koren et al., 2018).

The concept of RMS had emerged to cope with these challenges (Koren et al., 1999). RMS are designed for rapid changes in structure, aiming at adjust the production capacity and functionality within a product family to respond to sudden changes in manufacturing requirements. This enables the design of a "living" evolving factory that can be rapidly and cost-effectively reconfigured exactly when the market requires a change (Koren and Shpitalni, 2010). Therefore, RMS assume a relevant role in achieving responsiveness, which is a key enabler of competitiveness (Leitao et al., 2012).

In order to realise RMS, manufacturing companies should implement reconfigurability. Reconfigurability, in turn, is the ability to repeatedly change and/or rearrange systems' components in a cost-effective way (Setchi and Lagos, 2004). Such ability is essential to meet current impelling needs of manufacturing companies in terms of economic, environmental and social sustainability (Napoleone et al., 2018). Reconfigurability is enabled by core characteristics, such as modularity, integrability, customisation, convertibility, scalability and diagnosability, which can facilitate the design of manufacturing systems to be reconfigurable, by the use of hardware and software modules that can be integrated quickly and reliably (Koren, 2013). These core characteristics also allow achieving the system's functionality and scalability required for the production of a product family to meet market demands. Without them, the reconfiguration process will be lengthy or even impracticable (Koren et al., 1999).

In addition to that, the Industry 4.0 paradigm holds the promise of increased flexibility and speed, mass customisation, improved quality and enhanced productivity in manufacturing, enabling companies to deal with many challenges, such as increasingly individualised products, shortened time to market and high product quality (Zheng et al., 2018). Thus, it can be expected that the disruptive technologies proposed by this paradigm, such as cloud computing, internet of things, big data and analytics, augmented reality, mobile collaborative robotics and additive manufacturing, might significantly contribute to increase the reconfigurability of manufacturing systems (Maganha et al., 2018).

Reconfigurability can be implemented in different levels, such as workstation, system and factory levels (Andersen et al., 2015). This research is focused on the system level, that includes the design of RMS. The design process of RMS can be broken down into three phases (Oke et al., 2011):

- *Layout design*, which includes the choice of machines and the layout of the manufacturing system. The choice of machines is related to the selection of machines to be included in the layout. The layout of the manufacturing system concerns the layout problem, which is the assignment of the machines selected to their locations.

- *Design/selection of the material handling system.* This phase consists in determining the material handling system to be used, calculating the unit loads or batch size for the system, assigning specific equipment to departmental moves and developing the flow path for the system.

- *Control system specification.* It involves the interrelationship between workstations, machines in the workstations, components, tooling and manpower, besides the coordination at the auxiliary buffer of the direction of the material handling system and the acceptance and delivery of work in progress from one material handling system to another.

Designing RMS represents a significant challenge compared to the design of conventional manufacturing systems, such as dedicated and flexible manufacturing systems. Conventional manufacturing system design methods do not support the design of RMS, because they do not consider the core characteristics of reconfigurability neither the new specificity of RMS, such as multiple products variants and multiple product generations over its lifetime (Andersen et al., 2017). Despite this, there are relevant contributions to the design of RMS in the scientific literature (Al-Zuheri et al., 2016; Cedeno-Campos et al., 2013; Dahane and Benyoucef, 2016). However, in practice, the achievement of RMS, *i.e.* the implementation of reconfigurability on manufacturing systems, appears to be in an initial stage (Maganha et al., 2018; Spena et al., 2016). This may be due to the limited empirical focus of the existing literature, that seems to neglect how reconfigurability can be implemented in manufacturing systems, which makes it difficult to practitioners to realise it in real design solutions (Andersen et al., 2018a). Therefore, it is of the foremost interest of both, academics and practitioners, to fulfil this existing gap between theory and practice. This study is aimed at bridging this gap.

1.2 Research objectives

This research is structured from a generic to a specific context. It is composed of three main parts, each with specific objectives. The starting point is the concept of reconfigurability, which has been studied in the context of RMS. Despite the relevant research on this topic, it seems that there is no consensus regarding the number and types of reconfigurability core characteristics yet. Recently, the majority of authors points out six core characteristics of reconfigurability: modularity, integrability, customisation, scalability, convertibility and diagnosability. However, other characteristics, such as mobility, universality, compatibility and flexibility, have also been referred. In any case, the core characteristics of reconfigurability have not been tested empirically. This leads to the question of which are indeed the core characteristics of reconfigurability. A questionnaire survey was developed and applied to manufacturing companies based on Portugal intending to answer this issue. Besides allowing a better understanding of the core characteristics of reconfigurability, the answers to the questionnaire proposed enable conducting an exploratory analysis to verify the extent to which each of them is implemented in manufacturing companies, whether and how they impact on the operational performance of manufacturing systems and what are the needs of reconfigurability in manufacturing companies that use different business production strategies. In short, the first part of the thesis is intended to:

1. Understand the concept of reconfigurability, by identifying which are its core characteristics and to what extent each of them is present in manufacturing companies.

2. Investigate whether and how reconfigurability can affect the operational performance of manufacturing systems.

3. Investigate what are the needs for reconfigurability in manufacturing companies that adopt different business production strategies.

Reconfigurability can be implemented on manufacturing systems on different levels. The focus of this research is the system level, specifically, the reconfigurability addressed on systems design. As aforementioned, the RMS design process should consider three phases: the layout design, the design/selection of material handling system and the control system specification. In the first part of the thesis, all the three aspects are considered in the questionnaire to gain a better insight about reconfigurability. However, in the second part of the thesis, the focus is on the layout design problem, to avoid dispersion.

The layout design, considered within the RMS design process, must also cope with uncertainty and unpredictability in order to respond to market changes, such as fluctuations in demand volume and product mix. This means that, in RMS, the layout needs to be reconfigured and redesigned frequently as well. Moreover, the frequent redesign of the layout must be accomplished while the manufacturing system keeps high performances in terms of productivity, maintainability or quality. The potential of reconfigure layouts frequently, transforms the layout design from a strategic problem, in which only long-term material handling costs are considered, to a tactical problem, in which operational performance measures are considered in addition to the costs of handling materials and machine relocation when changing from one layout configuration to the next. Thus, RMS brings new challenges to the layout design problem aiming at achieving more reconfigurable systems. In the second part of the thesis, a systematic literature network analysis is conducted to identify these challenges. Thus, the second part of this thesis is aimed at:

4. Contribute to theory building on the layout design of RMS, identifying trends, evolutionary trajectories, key issues that have influenced the research to date and key areas for further study.

The novel technologies promoted by the advent of the Industry 4.0 are permeating the manufacturing industry, providing them the capacity to deal with sudden market changes and, consequently, the ability to leverage the reconfigurability of manufacturing systems. There are several technologies associated to the concept of Industry 4.0, but this thesis focuses on the use of mobile collaborative robotics. This technology can promote the share of tasks between humans and robots in the same workstation, giving rise to the concept of movable hybrid reconfigurable manufacturing systems (MH-RMS), *i.e.* manufacturing systems where humans and robots share the execution of tasks and where the robots are assumed to be mobile. This choice was made for two main reasons. First, mobile collaborative robots are highly adaptable resources, that can move whenever necessary, shifting their capacity to where it is requested. This is intimately related to the reconfigurable layout design, discussed in the second part of the thesis. Second, data about a company willing to introduce mobile collaborative robots in its assembly line were available, allowing to understand the impact of this technology on the reconfigurability of actual manufacturing systems. Therefore, the third part of this thesis intends to verify the impacts of introducing mobile collaborative robots, aimed at leveraging the reconfigurability of manufacturing systems, using an assembly line as case study. The objective of this last part of the thesis can be summarised as follows:

5. Analyse the impacts of introducing Industry 4.0 technologies, specifically mobile collaborative robotics, with the intention of leveraging the reconfigurability of manufacturing systems.

1.3 Research questions

The following research question (RQ) have guided the aforementioned objectives of this thesis:

- RQ1: To what extent reconfigurability is implemented in current manufacturing systems?

- RQ2: What are the impacts of reconfigurability on the operational performance of manufacturing systems?
- RQ3: What are the needs for reconfigurability on different business production strategies?
- RQ4: Which are the challenges posed by RMS for the layout design problem?
- RQ5: What are the impacts of the introduction of mobile collaborative robotics aimed at leveraging the reconfigurability of assembly lines?

1.4 Research methodology

This thesis adopts the MMA, as proposed by (Choi et al., 2016), in which two distinct research methods are employed to meet the research goals. This approach was chosen, because combining multiple methodologies allows to explore multiples perspectives of a problem, which increases the scientific merit of the study and contributes to the validation of the findings and conclusions.

The MMA follows a research methodology classification that includes: (a) analytical modelling (AM), whereby results are deduced from principles originated from computer science, economics, engineering, mathematics or physics, *e.g.*, using mathematical optimisation and simulation methods; (b) case study (CS), where results are generalised from detailed observations of practice; and (c) quantitative empirical (QE), which uses survey-based and statistical analyses (Sodhi and Tang, 2014). These methodologies can be combined in different ways to achieve the research objectives. In the AM-QE approach, the AM method and the QE method complement each other. One can first conduct a QE study then use the results to build models and conduct an AM analysis, or one can also build an analytical model, perform the analysis then conduct a QE study to support the theoretical findings. The AM-CS approach is especially valued for research that aims to advance industrial knowledge and practices (Chiu et al., 2011). In this case, the CS can provide motivation for the problem, offer data for theoretical analysis, validate the results and show real-world relevance. The QE-CS approach combines qualitative and quantitative data, which can improve the research rigor of the empirical research method. It allows the triangulation of data with different research approaches to overcome the bias issues that may merge with the use of a single research method (Choi et al., 2016).

To achieve the research objectives, this thesis uses the QE-CS approach. Research based on pure qualitative case studies is usually treated as a kind of exploratory work. On the other hand, CS alone is still not yet as popular as the other mainstream methods such as AM and QE studies (Choi et al., 2016; Sodhi and Tang, 2014). Thereby, these methods interact positively for achieving the research outcomes.

1.5 Thesis outline

This thesis is structured around the research questions. A summary of the thesis is shown in Figure 1.1, highlighting its structure, from the generic to the specific context and putting in evidence the research methodologies followed.

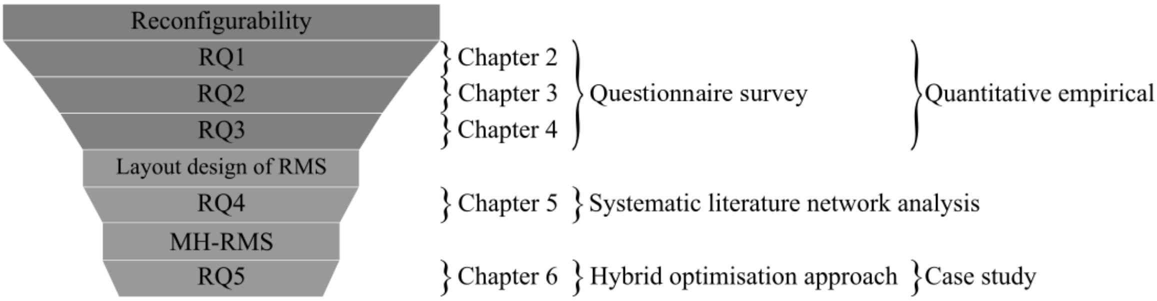

Figure 1.1: Thesis outline.

A description of its content, covering its chapters, is presented as follows:

Part II: Quantitative empirical approach

Understanding reconfigurability of manufacturing systems: an empirical analysis (Chapter 2). Six core characteristics are considered the enablers of reconfigurability by the majority of authors: modularity, integrability, customisation, convertibility, scalability and diagnosability. However, there is not a consensus regarding their number and types, and they had not been tested empirically. Therefore, a questionnaire survey is developed, based on these six core characteristics, to investigate the understanding of reconfigurability in manufacturing companies. This survey tests and validates the core characteristics of reconfigurability. An exploratory factor analysis is carried out to analyse the results (Forza, 2016). The implications of the implementation of the core characteristics are also discussed.

The impact of reconfigurability on the operational performance of manufacturing systems (Chapter 3). Findings from the questionnaire survey may help managers to decide which core characteristics should be implemented in their manufacturing systems. A confirmatory factor analysis is conducted to evaluate the goodness of measures, in terms of reliability and validity (Forza, 2016). After that, clustering methods based on cluster centroids are used to investigate the current level of reconfigurability implementation and its impact on the operational performance of manufacturing systems (Brusco et al., 2017).

An analysis of reconfigurability in different business production strategies (Chapter 4). This chapter is intended to analyse the implementation of reconfigurability in companies using different business production strategies, namely make-to-order, engineer-to-order, assembly-to-order and make-to-stock. An aggregated measure of reconfigurability is used to understand the needs of reconfigurability in these manufacturing companies (Anderson and Fornell, 2000). Some guidelines to improve the levels of reconfigurability implemented, considering the particularities of each production strategy analysed, are also presented.

Part III: Systematic literature network analysis

The layout design in Reconfigurable Manufacturing Systems: a literature review (Chapter 5). The layout design of RMS has been attracting increasingly attention in recent years, but a comprehensive literature review has not been presented. In response, this chapter provides a literature review, exploring the evolution of this research field through a systematic literature network analysis (Colicchia and Strozzi, 2012). A bibliometric and a chronological citation network analysis, more specifically, a main path analysis, are used to analyse the results, determine the current state-of-the-art and identify key areas for further research (Nooy et al., 2011).

Part IV: Case study

Leveraging the reconfigurability of assembly lines through mobile collaborative robots (Chapter 6). The novel technologies endorsed by the Industry 4.0 paradigm, such as mobile collaborative robotics, can be introduced on manufacturing systems aiming at leveraging their reconfigurability. In this chapter, the advantages and drawbacks of introducing mobile collaborative robots to improve the reconfigurability of an assembly line is analysed, based on a real industrial case. A model-based hybrid optimisation approach is used to solve the scheduling and layout problems in this assembly line (Klement, 2014). The results are then discussed highlighting the impacts of the introduction of mobile collaborative robots as a way to leverage assembly lines reconfigurability.

Part II Quantitative empirical approach

Contents

Chapter 2 Understanding reconfigurability of manufacturing systems: an empirical analysis

Published in *Journal of Manufacturing Systems*.

Abstract

The need for more responsive manufacturing systems to deal with high product variety and large fluctuations in market demand requires new approaches that enable the system to react to changes quickly and efficiently. Reconfigurability is an ability that allows the addition, removal or rearrangement of manufacturing system components and functions to better cope with high product variety and significant fluctuations in market demand in a cost effective way. This chapter empirically investigates the understanding of reconfigurability in industrial manufacturing companies and tests and validates its core characteristics using a questionnaire survey, which was carried out with Portuguese companies. Findings show the existence of five core characteristics of reconfigurability. The implications of these characteristics, concerning the implementation of reconfigurable manufacturing systems, are also analysed and discussed.

2.1 Introduction

In the 1980s, the concept of flexible manufacturing systems was introduced in order to respond to the need for mass customisation and greater responsiveness to the changes in products, production and market, driven by aggressive economic competition on a global scale, more demanding customers and the rapid pace of change in process technology (Kusiak, 1985; Maccarthy and Liu, 1993). A cost-effective response to market changes, which can be created by part family focus and customised flexibility, requires a manufacturing approach that is able to react to changes quickly and efficiently and that enables the operation of simultaneous tools (Koren et al., 1999). By the end of the 1990s, the concept of a RMS had emerged as an attempt to achieve responsive systems, capable of producing high quality products at low costs, by providing an adjustable structure, changeable functionalities, scalable capacity and flexibility (ElMaraghy, 2006; Koren et al., 1999, 2018). RMS are designed at the outset for a rapid change in structure to adjust the production capacity and functionality quickly within a part family in response to sudden changes in manufacturing requirements (Koren et al., 1999). An RMS is also designed to produce a particular family of products and to cope with situations where productivity and responsiveness are of vital importance. Its main components for machining are CNC machines and reconfigurable machine tools (RMT), which are controlled, coordinated and operated in an open-architecture environment (Koren et al., 1999).

In sum, at an operational/tactical level, reconfigurability can be seen as the ability to rearrange manufacturing elements in order to adjust to new environmental and technological changes (Abdi and Labib, 2003) and, at a tactical/strategic level, as an engineering characteristic that deals with the design of machines and systems for customised products in a cost effective market (Gumasta et al., 2011).

RMS assume a relevant role in manufacturing systems by providing a way to achieve a rapid and adaptive response to change, which is a key enabler of competitiveness (Leitao et al., 2012). Nowadays, disruptive technologies, such as cloud computing, internet of things, big data and analytics, augmented reality and additive manufacturing are permeating the manufacturing industry and making it smart and capable of addressing current challenges, such as increasingly customised requirements, improved quality, and reduced time to market (Zheng et al., 2018). Thus, it can be expected that these novel technologies, promoted by the concept of industry 4.0, might significantly contribute to increase the reconfigurability of manufacturing systems.

Several authors state that an ideal RMS should possess core characteristics to increase the speed of its responsiveness when faced with unpredicted events, such as sudden market changes or machine failures (ElMaraghy, 2006; Gumasta et al., 2011; Koren and Shpitalni, 2010; Wang et al., 2017). Nevertheless, there is no consensus regarding the number and types of RMS core characteristics yet. In fact, in Koren et al. (1999) five RMS characteristics are presented: modularity, integrability, customisation, convertibility and diagnosability. Later, in Nishith et al. (2013) scalability is introduced as a new RMS characteristic. These six characteristics have been considered as the core characteristics of RMS by most authors (Andersen et al., 2017; Benderbal et al., 2018b; Koren et al., 2018; Wiendahl et al., 2007). However, other different characteristics have been, to a lesser extent, put forward such as mobility, universality, compatibility, flexibility and self-abilities (*e.g.* self-adaptation) (ElMaraghy, 2006). Therefore, it is possible to consider that RMS must possess several distinct characteristics and that the sum of these characteristics determines the ease and the cost of reconfiguring manufacturing systems.

Several authors argue that RMS possess the advantages of both dedicated lines and flexible systems (Benderbal et al., 2017a; Koren and Shpitalni, 2010; Koren et al., 2018; Bi et al., 2008). Furthermore, Mehrabi et al. (2000a) present the challenges expected to be faced by manufacturing systems and how RMS will have a core role in responding to these challenges. Thus, it is expected that RMS will attract the interest of a large number of companies (Wang et al., 2017). Additionally, as the need for more reconfigurable systems increases, knowing the various characteristics of RMS becomes of foremost importance in the interest of the manufacturer to be prepared and equipped to evaluate and decide the extent of reconfigurability for their production systems (Gumasta et al., 2011). Therefore, a better understanding of RMS and their core characteristics is required to help companies to assess their present level of reconfigurability and to provide guidelines to improve it in either existing or new manufacturing systems.

Although RMS have been discussed over the last decades in the scientific literature, there are only a few empirical studies concerning how this concept could be transferred and implemented by industry. This chapter is intended to make a contribution to this understanding by conducting an exploratory survey to identify the core characteristics of RMS. The analysis was developed based on the six characteristics mentioned by the majority of authors that, despite being identified in the literature, had not been tested empirically. The survey results are analysed and discussed to assess to what extent each of the characteristics identified are present in the manufacturing systems of the companies surveyed. Furthermore, a discussion of how each of the core characteristics identified of RMS might be impacted by the novel technologies put forward by the concept of industry 4.0 is presented, providing insights into how they can contribute to increasing the reconfigurability of manufacturing systems.

The remainder of this chapter is organised as follows: Section 2.2 provides a literature review on the topic of RMS. Section 2.3 presents the research methodology and the analysis of reliability and validity of the questionnaire. The data collected are analysed and discussed in section 2.4. Finally, section 2.5 presents the conclusions, the limitations of this research and suggestions for future studies.

2.2 Literature review

The current production scenario, characterised by aggressive competition and rapid evolution in process technologies, requires more flexible, robust, reconfigurable and easily upgradable systems that rapidly adjust their production capacity and functionality, integrate new technologies and launch new product models quickly, supporting an agile response to the changing conditions through their dynamic reconfiguration on the fly (*i.e.* without stopping, reprogramming, restarting the processes or the other system components) (Leitao et al., 2012; Mehrabi et al., 2000a; Singh et al., 2017). In order to stay competitive, manufacturing companies must remain highly sensitive to market (fluctuations) and be able to react quickly to market changes by introducing products that meet customer needs in a timely manner and by producing high quality products at low costs (Koren et al., 2018; Wang et al., 2017).

A cost effective approach that encompasses these capabilities is RMS, whose capacity and functionality can be modified exactly when needed (Koren and Shpitalni, 2010). RMS are cost effective because they boost productivity and increase the lifetime of a manufacturing system (Koren et al., 2018). They are created at the design stage to be capable of making rapid changes in the structure and hardware/software components to adjust the production capacity and functionality quickly in response to sudden changes in irregular market demand (Wang et al., 2017). RMS may be able to overcome both dedicated manufacturing systems (DMS) and flexible manufacturing systems (FMS), by providing a significant reduction of costs and time in the launching of new products and in the integration of new manufacturing processes into existing systems (Renzi et al., 2014).

RMS are an attempt to achieve changeable functionality and scalable capacity, by proposing a manufacturing environment where components, machines, cells or material handling units can be added, removed, modified or interchanged as needed to respond quickly to changing requirements (Wiendahl et al., 2007). However, the objectives of RMS go beyond the rearrangement of its components. This type of system allows, inclusively, the reduction of the time required for designing new systems and for reconfiguring existing ones, and the rapid modification and integration of new technology or functions into existing systems. Additionally, RMS may contribute to the reduction of product costs, continuous improvement in product quality and increased flexibility and responsiveness (Koren et al., 2018; Mehrabi et al., 2000a).

Koren et al. (1999) proposed the concept of RMS and established that it must be designed using hardware and software modules that can be integrated quickly and reliably, thus facilitating the reconfiguration process. RMS should also use modular equipment to achieve the system functionality required for the production of a part family through scalability and reconfiguration as needed, when needed, to meet market demands (Benderbal et al., 2018b; ElMaraghy, 2006). To achieve these design goals, RMS must have some core characteristics.

When this concept emerged, five core characteristics were described and considered essential for RMS, namely modularity, integrability, convertibility, diagnosability and customisation (Koren et al., 1999). Several authors supported and enhanced these characteristics (Abdi and Labib, 2003; Mehrabi et al., 2000a; Renzi et al., 2014; Setchi and Lagos, 2004). Although Koren et al. (1999) and Mehrabi et al. (2000a) mentioned the increasing need for an adjustable structure for manufacturing systems, enabled by rapid changes in the system production capacity, scalability was only later introduced as another core characteristic of RMS (ElMaraghy, 2006). The six core characteristics of RMS considered by the majority of authors are described hereafter.

Modularity means that all its major components are modular (*e.g.* structural elements, axes, controls, software, hardware and tooling) and the compartmentalisation of operational functions into units can be manipulated between alternate production schemes for optimal configuration arrangement (Benderbal et al., 2018b; Koren et al., 1999; Koren and Shpitalni, 2010). *Integrability* is related to the ability to readily integrate these modular components, by a set of mechanical, informational and control interfaces that facilitate integration and communication, which also allow the future integration of new technologies (Koren and Shpitalni, 2010; Mehrabi et al., 2000a). *Customisation* has two main aspects: customised control, obtained through the integration of control modules with the aid of open-architecture technology, which provides the exact control functions needed; and customised flexibility, where machines are built around family parts and that provides only the flexibility needed to produce those specific parts (Koren et al., 1999; Padayachee and Bright, 2014). *Convertibility* is the characteristic that allows the system, in an operating mode, to change quickly between existing products or different batches, by changing tools, part-programs and fixtures, possibly requiring manual adjustment, allowing the system to adapt for future products. It also concerns the ability to transform the existing functionalities of machines to suit new production requirements easily (Koren et al., 1999; Mehrabi et al., 2000a). *Scalability* concerns the ability to modify production capacity incrementally by adding/removing resources or changing system components, rapidly and economically (ElMaraghy, 2006; Koren and Shpitalni, 2010; Koren et al., 2016). *Diagnosability* refers to the detection of unacceptable quality of parts and reliability problems, which are critical factors regarding the reduction of ramp-up time in RMS. As production systems become more reconfigurable and are modified more frequently, the ability to read the current state of a system to detect and diagnose the root cause of output product defects automatically and then quickly correct operational defects, becomes essential in order to rapidly tune the newly reconfigured system (Koren et al., 1999; Koren and Shpitalni, 2010; Mehrabi et al., 2000a).

As mentioned previously, although RMS have been discussed over the last decades, there are only a few empirical studies concerning how this concept could be transferred and implemented by industry. Some efforts have been made to quantify some of the core characteristics of RMS. A study on diagnosability measures throughout the total life cycle and integrating the system's design and manufacturing process, was conducted by Liu et al. (2000), and resulted in a diagnosability index to evaluate and control quality defects of products and equipment failures. Maier-Sperredelozzi et al. (2003) proposed metrics to evaluate the convertibility of production systems and of machines, based on assessments of convertibility itself, which were applied to an industrial case that compared the convertibility of two different configurations of a system. Gumasta et al. (2011) developed a reconfigurability index, considering modularity, scalability, convertibility and diagnosability, conducting an illustrative example to enlighten the developed methodology. Farid (2017) considered integrability, convertibility and customisation to discuss how these characteristics fit the requirements for reconfigurability measures in manufacturing systems. Wang et al. (2017) developed an evaluation index system for RMS reconfiguration schemes, which was initiated based on the six key RMS characteristics. Regarding the questionnaire-based methodology, research has been restricted to the identification of trends and perspectives for RMS (Mehrabi et al., 2002) and to the identification of the key requirements for the design of changeable manufacturing and assembly systems (Spena et al., 2016). Despite these attempts to assess reconfigurability through its core characteristics, none has empirically tested or validated the existence of those core characteristics. For this reason, this chapter reports an empirical research, more specifically, a questionnaire survey, that was conducted with Portuguese manufacturing companies to identify the core characteristics of RMS.

2.3 Research methodology

2.3.1 Survey development and data collection

The aim of the proposed survey is to analyse the understanding of reconfigurability and its core characteristics on manufacturing systems empirically. Considering the competitive production environment, manufacturing companies should be able to react rapidly and cost-effectively to unpredictable changes that occur at an increasing pace, such as large fluctuations in product demand and in product mix (Koren, 2013). The reconfiguration process requires major changes in complete cells and systems, as well as in the software used for planning and controlling processes and production. All this adds to the ever growing complexity of products, processes, manufacturing systems and enterprises (ElMaraghy, 2006). Consequently, these changes can affect the performance of the current layout configuration, triggering the need to rearrange resources for the next production period (Meng et al., 2004). Taking this into account, the first part of the survey (Appendix A) was developed to characterise respondent companies, seeking to understand: the level of complexity of their products, operations and bill of materials (BOM); the extent of the variability in demand or product mix and the objectives and frequency of layout rearrangement.

The second part of the questionnaire concentrated on questions regarding the core characteristics of reconfigurability. The research team developed the questionnaire supported on the literature. All items were measured using a 7-point Likert scale, with the responses ranging from 1 (strongly disagree) to 7 (strongly agree). Table 2.1 shows the references of these constructs.

Table 2.1: Reconfigurability items used.

Items	References
Modularity	
The major equipment in our manufacturing system can be easily added to, or removed from, the shop floor Our equipment is made of several functional modules that can be easily added/removed The major equipment in our manufacturing system can be easily reorganised to obtain an adapted configuration to manufacture new products Our material handling system (between workstations) allows an easy rearrangement of the process flow, by adding/ignoring operations, according to the product to be manufactured Our manufacturing system is composed by hardware and software modules that can be integrated quickly and reliably	Koren et al. (1999); Mehrabi et al. (2000a); Koren and Shpitalni (2010); Koren (2013); Nishith et al. (2013); Setchi and Lagos (2004)
Integrability	
We can integrate equipment rapidly and precisely by a set of mechanical, informational and control interfaces in our production system Our equipment is operated/coordinated by an integrated control system, exploited in an open-architecture environment Our manufacturing system allows an easy integration of new equipment and new technologies Our equipment and our control system were designed with interfaces that facilitate the integration of new components	ElMaraghy (2006); Farid (2017); Koren and Shpitalni (2010); Mehrabi et al. (2000a); Nishith et al. (2013)
Customisation	
The location of our equipment on the shop floor was chosen considering the need to produce an entire product family Our manufacturing system's capacity and flexibility (hardware and control system) were designed to match the production needs of a product family Our control system, supported by an open-architecture technology, can be customised to have the exact control functions needed	Farid (2017); Koren et al. (1999); Mehrabi et al. (2000a); Nishith et al. (2013)
Convertibility	
The capacities of our manufacturing system and of our equipment can be easily transformed to respond to changes in production requirements We can easily stop an equipment operation and reconfigure its functions to manufacture a new product type We can change quickly from the manufacturing/assembling one product to another, if they are from the same family Our manufacturing system allows for an easy switch between existing products and can adapt to new/future products	ElMaraghy (2006); Farid (2017); Koren et al. (1999); Koren and Shpitalni (2010); Maier-Sperredelozzi et al. (2003); Mehrabi et al. (2000a)
Scalability	
Our production capacity can be changed by adding/removing equipment or by changing the system's components Our manufacturing system can easily respond to unexpected equipment failures We can easily add equipment, at any stage of the production process, without interrupting operations for long periods Our throughput can be changed to respond to changes in demand in a relatively short time	ElMaraghy (2006); Koren and Shpitalni (2010); Nishith et al. (2013); Wang and Koren (2012)
Diagnosability	
Our manufacturing system can automatically detect defective products, diagnose their root causes and reset its parameters to restore the initial situation Our manufacturing system includes inspection resources that allow the detection of quality defects in real time Our manufacturing system uses inspection equipment that can be easily reconfigured for use in different stages of the production process In a start-up phase, we can adjust the manufacturing system parameters, thus reducing the ramp-up time, because we have mechanisms that allow a quick diagnosis of problems with quality Our manufacturing system can automatically identify the source/cause of failures or problems with quality	ElMaraghy (2006); Koren et al. (1999); Koren and Shpitalni (2010); Liu et al. (2000); Mehrabi et al. (2000a); Nishith et al. (2013)

After the development of the items, a two-member panel of academic experts with extensive industrial management experience and cognisance of Portuguese manufacturing companies, and a Scientific Committee specialised in this field of study were requested to review the questionnaire critically and make comments and suggestions for its improvement. The questionnaire was presented in a meeting of a research project, focused on industry 4.0, to a group of eight academics and managers from three universities, two research centres and 3 companies, who contributed to the improvement of the clarity of the questions. It was suggested that a combination of phone contact and online approach would affect the response rate and data quality positively. Since managers from 3 manufacturing companies were present in the meeting and had prevented the inclusion of obvious questions and provided feedback on what could affect whether and how the targeted respondents would answer the questions, a pilot test was conducted only on two companies before the final dissemination. The pre-tested companies were asked whether the instructions and the questions were clear, whether there were any problems understanding what kinds of answers were expected or in providing answers to the questions asked and whether the planned administration procedure would be effective.

Following the experts', the Scientific Committee's and Dillman (2007) recommendations, companies were contacted by phone to identify the respondents and to introduce the objectives of the study. An electronic survey (e-survey) was developed, but the access link to the questionnaire was e-mailed exclusively to the target respondents. The main advantages of this data collection method are the lowest relative cost and the ease of securing information. However, the e-survey usually has lower response rates than other survey methodologies (Forza, 2016). To ensure a satisfactory response rate a reminder e-mail was sent to urge non-respondents to complete the survey if they had not done so already two weeks after the first contact. Then, two weeks after that reminder, a final appeal was sent to non-respondents. A summary of the survey results was promised to the respondents, evaluating the extent of reconfigurability in their companies.

2.3.2 Response rate and characterisation of respondents

The questionnaire targeted 600 Portuguese manufacturing companies and subsidiaries of multinational companies operating in Portugal. The 600 manufacturing companies were randomly selected from an initial list of 11000 organisations to construct the sample, which was mainly obtained from the Sabi database (`https://www.bvdinfo.com`). The companies selected are currently in operation and have an annual turnover of more than 1 million euros. The selection covers manufacturing companies from different industrial manufacturing sectors and are clustered according to their sizes, namely micro- (<10 employees), small- (10 to 49 employees), medium-sized (50 to 249 employees) and large companies (>250 employees), yielding a heterogeneous sample (European Comission, 2005). This approach was used to ensure a moderate level of external validity and to contribute to the generalisation of the results (Forza, 2016). The preferred target respondents were the managers with direct involvement in operational and strategic decision-making and knowledge of production processes and strategies. From the survey distribution, 7 companies did not respond to the questionnaire, because it was against the companies' policies and 288 did not give any response or justification. In total, 305 responses were received, of which 193 were incomplete, *i.e.* the respondent did not answer all the questions. Consequently, there were 112 usable responses from a population of 600 companies, representing an overall response rate of 18.7%. Table 2.2 summarises detailed data about the composition of the sample and respondents.

Table 2.2: Sample characteristics.

Characteristic	Frequency	%
Number of employees		
<10	8	7.0
10 to 49	28	25.0
50 to 249	52	46.4
>50	24	21.4
Total	112	100
Respondent's job title		
General manager	31	27.7
Production manager	17	15.2
Quality manager	11	9.8
Factory manager	9	8.0
Process engineer	8	7.1
Industrial manager	7	6.3
Maintenance manager	3	2.7
Other	26	23.2
Total	112	100

The most common layout configuration is the process layout (55.4%), followed by product layout (25.9%) and cellular layout (18.8%). Referring to the frequency of layout rearrangement (Table 2.3), respondents reported that production layout is not modified frequently, *i.e.* the system's structure is predominantly fixed. However, when a layout change occurs, the impact on lead time and throughput are more important than the impact on material handling costs and work in progress levels.

2.3.3 Characterisation of production systems and layouts

The respondent companies were also asked about their business production strategies and the type of production layout. The most commonly adopted strategies are MTO (51,8%), engineer-to-order (ETO) (19.6%), assembly-to-order (ATO) (17.0%) and make-to-stock (MTS) (11.6%). The majority of the companies surveyed seems to have a high level of

Table 2.3: Measures of complexity and flexibility in the companies surveyed.

Scales	Mean	Standard deviation (SD)
Complexity		
of operations	5.02	1.74
of BOM	4.60	1.94
of products	4.17	2.10
Supply chain characteristics		
Changes in product mix	4.36	1.88
Variations in supply requirements	4.20	1.825
Demand fluctuation	4.04	1.80
Volume fluctuation	3.79	1.76
Technical modification of products	3.79	1.82
Modifications to parts/components (by suppliers)	2.29	1.74

customisation, since the most applied business production strategies implies that assembly and manufacturing operations, or even the products' design, only start after receiving firm orders from the customers. Regarding the complexity, the results show complex operations, BOM and products. To understand the characteristics of the supply chain that companies face, they were asked about several criteria (Table 2.4). The majority of the respondents reported that changes to product mix, variations in supply requirements and demand fluctuations occur on a weekly basis, while volume fluctuations, technical modifications of products and modifications to parts/components by suppliers are less frequent. These results highlight the need for a highly responsive system, able to respond quickly to sudden market changes.

Table 2.4: Frequency and criteria considered when changing layout configuration.

Scales	Mean	SD
Frequency		
Layout modification	2.98	1.81
Criteria		
Lead time	5.21	1.57
Throughput	5.16	1.67
Material handling costs	4.45	1.75
Work in progress	4.32	1.70

2.3.4 Reliability and validity analysis

The goodness of measures is evaluated according to reliability and validity. The lack of reliability introduces a random error while the lack of validity introduces a systematic error (Carmines and Zeller, 1979). Reliability refers to the stability and the consistency in the measurement score and indicates dependability, predictability and accuracy, because it refers to the extent to which a measuring procedure achieves the same results in repeated trials (Forza, 2016). In this research, the internal consistency method was used to assess the reliability. In order to assess the internal consistency of the scales, Cronbach's coefficient alpha (α) was calculated. It is expressed in terms of the average inter-item correlation $\overline{\rho}$ among the n measurement items in the instrument under consideration (Cronbach, 1951), as follows:

$$\alpha = \frac{n\overline{\rho}}{1+(n-1)\overline{\rho}}$$

The alpha value of 0.7 is often considered the criterion for internal consistency for established scales, but the value of 0.6 is acceptable in the case of newly developed measures. An $\alpha \geq 0.8$ indicates that the measure is very reliable (Nunnally and Bernstein, 1994). Although the cut-off levels for exploratory research are less stringent, in this study, an $\alpha \geq 0.6$ was considered as the criterion, due to its exploratory nature (Hair et al., 2010).

Regarding the internal consistency, the sample size is an important factor, because significance tests were developed for large samples. A sample size of 30 or more is statistically sufficient to calculate the alpha, but it is possible to have more confidence in the accuracy considering large samples (Nunnally and Bernstein, 1994). This study sample of 112 respondents permitted alpha values that ranged from 0.731 to 0.841, which indicates a good level of reliability. Validity concerns the extent to which the instrument captures what it is intended to capture. The content validity refers to the degree to which the meaning of a set of items represents the domain of the concept under investigation, while the construct validity refers to the degree to which the scores obtained using a set of items behave as expected. The items of this survey questionnaire were constructed based on a literature review and experts' consultancy. Considering their feedback, extra items were eliminated, assuring that the core characteristics of reconfigurability were properly measured. After a pilot study a few modifications were made to the questionnaire, making it more understandable. Since all this involved field-based content validation, the measures could be generally considered to have content validity (Malhotra and Grover, 1998).

To assure the construct validity, the first property to check is the construct's unidimensionality. To be considered unidimensional, an empirical indicator must be significantly associated with an underlying latent variable and with only one latent variable. Evaluating unidimensionality can be performed numerically with an exploratory factor analysis (EFA) (Forza, 2016). An EFA by principal components with an orthogonal rotation (varimax) was conducted for the reconfigurability characteristics. The factor analysis had five eigenvalues greater than one, suggesting the presence of five factors, and a total variance explained of 65%. The rotated solution was examined to determine if the items in a scale that loaded on more than one factor were meaningful or unwanted nuisance factors. Those which were a nuisance or which represented more than one domain were eliminated. Also, the factor loading of items that did not exceed the generally recommended minimum value of 0.4 were discarded (Hair et al., 2010). Then, Cronbach's alpha was recalculated and the remaining items were refactored. Table 2.5 demonstrates the final version of the scales.

Table 2.5: Scales' validity and reliability.

Scale	Items	α	Loading	Mean	SD
Customisation	3	0.73		4.83	1.12
Our manufacturing system's capacity and flexibility (hardware and control system) were designed to match the production needs of a product family			0.85	5.02	1.38
The location of our equipment on the shop floor was chosen considering the need to produce an entire product family			0.83	5.14	1.34
Our control system, supported by an open-architecture technology, can be customised to have the exact control functions needed			0.74	4.34	1.44
Adaptability	7	0.82		4.59	0.99
We can easily stop an equipment operation and reconfigure its functions to manufacture a new product type			0.79	4.53	1.64
We can easily add equipment, at any stage of the production process, without interrupting operations for long periods			0.73	4.07	1.49
We can change quickly from the manufacturing/assembling of one product to another, if they are from the same family			0.73	5.22	1.46
Our manufacturing system allows for an easy switch between existing products and can adapt to new/future products			0.71	4.96	1.34
Our manufacturing system can easily respond to unexpected equipment failures			0.63	4.36	1.30
Our throughput can be changed to respond to changes in demand in a relatively short time			0.60	4.69	1.36
The capacities of our manufacturing system and of our equipment can be easily transformed to respond to changes in production requirements			0.51	4.31	1.43
Diagnosability	5	0.85		3.98	1.27
Our manufacturing system can automatically identify the source/cause of failures or problems with quality			0.81	3.63	1.66
In a start-up phase, we can adjust the manufacturing system parameters, thus reducing the ramp-up time, because we have mechanisms that allow the quick diagnosis of quality problems			0.78	4.16	1.46
Our manufacturing system includes inspection resources that allow the detection of quality defects in real time			0.76	4.51	1.55
Our manufacturing system uses inspection equipment that can be easily reconfigured for use at different stages of the production process			0.75	3.98	1.64
Our manufacturing system can automatically detect defective products, diagnose their root causes, and reset its parameters to restore the initial situation			0.74	3.47	1.83
Integrability	4	0.83		3.63	1.23
Our equipment is operated/coordinated by an integrated control system, exploited in an open-architecture environment			0.86	3.27	1.60
Our equipment and our control system were designed with interfaces that facilitate the integration of new components			0.80	3.77	1.49
We can integrate equipment rapidly and precisely by a set of mechanical, informational and control interfaces in our production system			0.67	3.34	1.51
Our manufacturing system allows for an easy integration of new equipment and new technologies			0.67	4.15	1.43
Modularity	3	0.81		3.51	1.20
Our equipment is made of several functional modules that can be easily added/removed			0.85	3.16	1.58
The major equipment in our manufacturing system can be easily added to, or removed from, the shop floor			0.83	3.01	1.70
The major equipment in our manufacturing system can be easily reorganised to obtain an adapted configuration to manufacture new products			0.74	3.36	1.67

2.4 Data analysis and findings

2.4.1 Exploratory Factor Analysis

The factor analysis (Table 2.5) shows that the companies surveyed distinguish five core factors. The items concerning convertibility and scalability have loaded on the same factor, meaning that these characteristics are interpreted as a single one. For a manufacturing system to be reconfigurable, it must be capable of modifying functionality and/or capacity, in a cost effective and timely manner. The system must be easily convertible from one product to another and the production capacity must be readily scalable to produce more products on the existing system, exactly when the market needs them (Koren, 2013). Convertibility is the system's ability to adjust production functionality quickly or change from one product to another (Maier-Sperredelozzi et al., 2003). Scalability allows the system's throughput capacity to be readily adjusted to abrupt changes in market demand (Koren et al., 2016). These characteristics differ in that convertibility concerns the transformation of a system's functionalities while scalability concerns the modification of production capacity. Besides this, convertibility includes contributions concerning machines, their arrangements or configuration and material handling devices, and scalability refers to the adjustment of structure, at the system level (adding or removing machines) and at the machine level (changing a machine's hardware and control software, *e.g.* adding spindles, adding axes, or changing tool magazines) (Koren, 2013). However, these core RMS characteristics may merge because both are directly related to a manufacturing system's responsiveness to sudden changes: convertibility to changes in product mix and scalability to changes in demand. Additionally, both characteristics must be considered at the project stage of RMS, which must be designed at the outset for future expansion in its functions and throughput capacity, to enable changes in supply exactly when needed by the market (Koren et al., 2016).

The existence of five core characteristics regarding a system's reconfigurability is supported by the early studies on RMS, which considered modularity, integrability, customisation, convertibility and diagnosability as the essentials (Abdi and Labib, 2003; Koren et al., 1999; Mehrabi et al., 2000a; Setchi and Lagos, 2004). Nevertheless, these first definitions of convertibility concerned only the changeover between products and batches, changes of tools, part-programs and fixtures, and system adaptations for new products. Despite considering the structural adjustment at the machine level, which is a partial description of scalability, they did not include the needs at the system level, *i.e.* the addition or removal of resources to readily adapt the system's throughput capacity for future expansion. For this reason, the description of convertibility does not fit that construct that merged convertibility and scalability measures. A more suitable definition, gathering and generalising both main abilities, is adaptability, that can be defined as the property of a manufacturing system that enables it to adapt its capacity and functionality by means of an adjustable structure to changed or new situations. This permits a short term resetting of the system to produce different variants of current products or new products, and guarantees a high long-term benefit-to-cost-ratio (Koren et al., 1999). Adaptability is commonly related to a system's arrangement and its physical configuration, and is considered at the system's design stage, as well as convertibility and scalability.

Modularity factors are supposed to measure whether manufacturing equipment is composed by modules that can be easily reorganised, added to, or removed from, the shop floor to obtain an adapted configuration of the production system. Integrability items attempt to identify whether companies are capable of integrating new technologies or equipment in the existing production system and the existence of an integrated control protocol. The aim of customisation is to verify whether the production system was designed based on a product family that has the exact control functions needed. Diagnosability is intended to identify whether the manufacturing system includes inspection resources that allow the detection of failures or problems with quality in real time. The results obtained regarding these factors are aligned with findings in the literature and their positioning is discussed in the next section.

2.4.2 The implementation level of RMS core characteristics

In Table 2.5, a summary of the respondents' perceptions of the implementation level of the variables investigated is presented. These core characteristics determine the time, the effort and the cost of the reconfiguration process and enable a rapid response to sudden market changes (Koren et al., 1999; Koren and Shpitalni, 2010).

For the companies surveyed, the characteristic ranked in first place was customisation, which is coherent due to the business production strategies most adopted. This means that the capacity and the flexibility of their manufacturing system and the placement of equipment were designed around a part/product family, with enough customised flexibility to manufacture all members of that family, and that the control system provides the exact control functions required. The characteristic ranked second was adaptability, meaning that the companies surveyed are capable of adjusting the functions and throughput capacity of their systems to respond to unpredictable changes in production requirements and market demand. In addition, the companies are able to stop the operation of a machine and reconfigure its functions, respond to unexpected equipment failures and add equipment at any stage of the production process, thus allowing an easy switch between existing products and the adaptation to new or future products. Adaptability should also be considered at the design stage of the system, but it is less implemented than customisation, because it may require an initial investment to allow future convertibility and scalability actions. However, being capable of reconfiguring functions and incrementing capacity by the exact amount, exactly when the market requires, may reduce costs in the long term.

Diagnosability was the characteristic ranked third. The manufacturing systems of the respondent companies include inspection resources that allow the detection of quality or reliability problems and defective products in real time, as well as the diagnosis of their root causes and the resetting of their parameters to restore the initial situation or adjust its parameters. A rapid tuning to new conditions is essential to produce quality products. Indeed, performing in-process diagnostics may dramatically shorten the ramp-up time after reconfigurations and it allows the rapid identification of problems with quality and reliability during normal production. Additionally, the respondents perceive lower implemented levels of integrability and modularity. The majority assumed that companies have difficulties in easily, rapidly and precisely integrating a control system, new equipment or new technologies. Ideal RMS are able to integrate machine tools, sub-assemblies and sub-systems in changed manufacturing scenarios, exchange real time information, including their status and become participative in enhancing system efficiency (Singh et al., 2017).

The lack of machine tool design methodology and the lack of interfaces increase the barriers that impede modularity (Koren et al., 1999). These are possible reasons why modularity was listed as the least ranked characteristic. The companies surveyed reported that the most important equipment is not composed by modules, cannot be easily reorganised to obtain an adapted structure to manufacture new products, nor be easily added or removed from the shop floor. Despite the aim to develop designs with different detachable modules for rapid and easy reconfiguration, efficient upgradation and other engineering objectives, each objective may require different modularisation, thus increasing the costs of the implementation of modularity (Singh et al., 2017).

While customisation and adaptability reduce reconfiguration costs and were considered as critical characteristics of RMS, diagnosability, integrability and modularity support RMS characteristics, minimise reconfiguration time and effort and allow rapid reconfiguration, but they do not guarantee modifications in production capacity and functionality (Gumasta et al., 2011; Koren and Shpitalni, 2010). Note that the two critical characteristics of reconfigurability (customisation and adaptability) appear to be more implemented than the other three characteristics (modularity, integrability and diagnosability). A T-test was performed showing that there is a statistical significant difference, at a 99% level, between the means of the two first variables and of the last three variables.

Hence, it is possible to say that production systems seem to be prepared to be reconfigurable, but they lack the characteristics that allow for a rapid reconfiguration, making reconfigurability difficult to achieve (it is possible, but it implies interrupting production for long periods and, consequently, high costs). As a rule, these three characteristics that are less present in manufacturing systems are also the hardest and the most expensive to implement.

Novel technologies preconized in the concept of industry 4.0 might help to increase the level of implementation of these three RMS core characteristics. In fact, in industry

4.0, production systems evolve to cyber physical production systems (CPPS), which comprise smart machines, warehousing systems and production facilities that have developed digitally and feature end-to-end integration. By using data analytic tools, control charts statistical knowledge and intelligent algorithms, data can be processed to provide valuable information for manufacturers (Zheng et al., 2018). These technologies and the principle of 3D scanning for automated quality inspection may contribute to real time processing, enabling diagnosability. However, these technologies possesses drawbacks, such as the high cost of the devices, limited point per second scanning volume, and need for high-capability hardware for data processing (Zheng et al., 2018).

Although integrability implies a mutual information and communication system for all equipment and organisational functions, the current production scenario in many companies seem to have multiple protocols, with the associated problems that this may bring. CPPS can bring together virtual and physical worlds to create a truly networked world in which intelligent objects communicate and interact with one another. Thus, standardised data communication protocols and information modelling methods may be used to address this issue (Zheng et al., 2018). On the other hand, integrability also needs mechanical and physical systems, including transportation systems, which ease the introduction of new equipment. The use of radio frequency identification devices (RFID), sensors and cameras attached to critical components could facilitate the collection and transmission of real time data. Compatible information systems, reconfigurable controls and more flexible transportation systems, *e.g.* automated guided vehicles (AGV), could also contribute to the increase of the systems' integrability. In addition, an open and integrated environment may enhance the data acquisition capabilities of devices and applications, and move towards a plug-and-play environment to reduce the cost of data integration (Zheng et al., 2018).

Finally, modularity is still difficult to find in the majority of manufacturing equipment, although it is a key factor and should be included in the design phase. Lightweight equipment and mobile and collaborative robotics that facilitate rapid and easy addition to, or removal of, robots from tasks, may contribute to reinforcing this ability. Furthermore, technological advances in the field of industry 4.0 may overcome the difficulties of having a harmonised human-machine environment, which allows effective and profitable co-existence and cooperation (Benderbal et al., 2018b; Andersen et al., 2017).

Modular-based systems have many benefits that will make it possible to achieve the paradigm of reconfigurable manufacturing systems and the necessary mass customisation. Due to its modularity, it is possible to achieve sufficient variety by combining different modules while significantly reducing the number of parts that need to be produced for a product family. Moreover, if the modularity is incorporated in the design process from the outset, the life cycle cost will be decreased. The greater the modularity is, the lower the life cycle cost will be, where standardised module interfaces have a positive impact as they harmonise the work content (Benderbal et al., 2018b).

2.5 Conclusion and further research

This research focused on an empirical analysis of reconfigurability in manufacturing systems, by measuring the extent to which the core characteristics of RMS are implemented. The questionnaire survey was conducted with 600 Portuguese manufacturing companies and 112 usable responses were obtained, representing a response rate of 18.7%. The reliability and validity achieved provide tentative evidence that this measurement instrument is reliable and valid. Reliability was demonstrated with Cronbach's alpha values, which all exceeded 0.7, four of them, namely: diagnosability, integrability, adaptability and modularity, obtained Cronbach's alpha values of ≥ 0.8. Construct validity, assessed by an EFA, showed that all factor loadings exceeded the threshold value defined.

Although RMS have been discussed over the last decades and some efforts have already been made to measure the reconfigurability of manufacturing systems, none have empirically tested or validated the core characteristics or has used a survey research methodology. This investigation represents the first effort using exploratory survey research that tests the core characteristics of RMS. The findings support the existence of five core characteristics of reconfigurability instead of the six predicted in the literature. Convertibility and scalability merge and are understood as one unique dimension, because both are directly related to a manufacturing system's responsiveness to abrupt changes and future market conditions, and both must be considered at the design stage of reconfigurable systems.

The results make it possible to understand the level of implementation of each RMS core characteristic in the companies surveyed. Customisation and adaptability, which have been considered critical reconfiguration characteristics, have a higher level of implementation than diagnosability, integrability and modularity, which enable a rapid reconfiguration but without guaranteeing modifications in production capacity and functionality. Thus, the findings show that while production systems seem to be prepared to be reconfigurable, they lack the characteristics that allow for a rapid reconfiguration.

Customisation seems to be the easiest characteristic to implement, while modularity the hardest. Despite allowing a rapid reconfiguration, modularity may also require additional investment, because different and various modules may be needed to compartmentalise operational functions. It can be concluded that manufacturing companies tend to prioritise the implementation of characteristics and practices that reduce the overall costs.

The findings seem to suggest that the novel technologies preconized by the concept of industry 4.0, such as big data analysis and real time collection, flexible transportation systems or mobile and collaborative robotics, might significantly contribute to the increase of manufacturing systems reconfigurability. In practical terms, the questionnaire developed can be used by managers to assess the degree of reconfigurability of their production systems and for internal and external benchmarking. Furthermore, this chapter highlights some current technological advances, discussing how they can contribute to improve each of the core characteristics of RMS. The sum of RMS core characteristics determines the ease and the cost of reconfiguring manufacturing systems. Thus, knowing the level of implementation of each core characteristic and how each one can be improved might help managers to decide strategies to increase the reconfigurability of their production systems.

The data for this survey were collected from firms based in Portugal. This is a limitation of this study and, therefore, the replication of this questionnaire in other countries is recommended for future research in order to confirm its findings. Other directions for further studies concern the validation of this research instrument using a confirmatory analysis and the analysis of the relationship among the characteristics of reconfigurability, layout configurations and performance indicators. The questionnaire proposed could also be the basis for the development of an index to measure reconfigurability. Future research should be directed at the core characteristics of RMS, which seem to be implemented to a lesser extent in the companies surveyed (diagnosability, integrability and modularity), seeking to identify solutions to improve their level of implementation. Finally, it would be interesting to understand how the core characteristics of RMS interact (*e.g.* whether they possess similar/different behaviour or whether one impacts positively/negatively on another).

Chapter 3 The impact of reconfigurability on the operational performance of manufacturing systems

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Abstract

Purpose – The aim of this paper is to investigate the current level of reconfigurability implementation and its impact on manufacturing systems' operational performance empirically.

Design/methodology/approach – This study is based on a questionnaire survey. Statistical analysis procedures were adopted to accomplish its objectives, namely clustering methods based on cluster centroids. An ANOVA analysis was used to test for cluster differences among the variables.

Findings – The results show that the manufacturing companies surveyed can be divided into three clusters, with different levels of reconfigurability implemented. The implementation of the core characteristics of reconfigurability depends on the product's complexity and demand variability, in terms of volume and product mix, as these have an impact on the operational performance, in terms of quality, delivery and flexibility.

Research limitations/implications – The data for this survey were collected from manufacturing companies based in Portugal. Therefore, the replication of this questionnaire in other countries is recommended for future research to confirm its findings.

Practical implications – The questionnaire developed could be used by managers to assess the level of reconfigurability of their production systems and for internal/external benchmarking. The findings may help managers to decide which core characteristics should be implemented in their manufacturing systems.

Originality/value – The majority of the research addressing performance issues in reconfigurable manufacturing systems has been applied to case studies. This research reports an empirical investigation using questionnaire-based methodology to provide generalisable empirical evidence.

3.1 Introduction

In an increasingly competitive world, companies recognise the need to permanently develop new and more sophisticated strategies, in order to maintain and increase their performance (Azevedo et al., 2016). Performance issues are crucial for companies to understand the state of their manufacturing systems and to take suitable action to keep their competitiveness (Hasan et al., 2014). RMS are designed for rapid changes in structure, to adjust the production capacity and functionality in response to sudden changes in manufacturing requirements (Koren et al., 1999). This type of system has been widely acknowledged as suitable for handling performance issues as well as situations where productivity and responsiveness are of vital importance. Indeed, RMS play a key role in responding to the current challenges faced by industries, contributing to the improvement of the systems' global performance (Benderbal et al., 2017a; Bi et al., 2008; Koren et al., 2018; Singh et al., 2017).

In RMS, reconfigurability is an important ability that determines the ease and cost of reconfiguration. It can be implemented at the levels of equipment, manufacturing and systems to efficiently and dynamically change the functionality and capacity boundaries of the system, with limited effort (Andersen et al., 2018a). Implementing reconfigurability to accommodate product variety, customisation, small batch sizes, fluctuating market demand and the frequent introduction of new products can provide capacity and functionality on demand, thereby reducing the trade-off between productivity and flexibility (ElMaraghy, 2006; Koren and Shpitalni, 2010). However, approaching reconfigurability as a universal concept or absolute feature of a manufacturing system is inadequate, as it has various different characteristics that can be designed in unlimited ways to provide context-specific and appropriate ability to cope with changes (Andersen et al., 2017). Several authors state that ideal RMS can achieve reconfigurability when possessing core characteristics that increase the speed of its responsiveness when faced with unpredicted events, such as sudden market changes or machine failures (Wang et al., 2017). At a tactical level, reconfigurability can be seen as the ability to rearrange manufacturing elements in order to adjust to new environmental and technological changes (Abdi and Labib, 2003). At a strategic level, as an engineering characteristic that deals with the design of machines and systems for customised products in a cost effective way (Gumasta et al., 2011).

Previous studies on RMS have emphasised numerous aspects, such as reconfigurable machines, design methodologies, the selection of machines, machine layout and optimal configuration (Andersen et al., 2017; Benderbal et al., 2017b, 2018b; Goyal et al., 2013; Youssef and ElMaraghy, 2007). Nevertheless, there are many barriers concerning the design of RMS. When designing this type of system, it is essential that manufacturing companies select and implement the right core characteristics in accordance with their specific requirements (Andersen et al., 2018a). Thus, knowing the various characteristics of RMS is of foremost importance for manufacturers to be prepared and equipped to evaluate and decide the extent of reconfigurability necessary for their production systems, while considering their business, manufacturing and change strategies (Francalanza et al., 2016; Gumasta et al., 2011).

Moreover, in order to measure the performance of RMS, their core characteristics should be considered, because they essentially reflect the properties of the system (Gumasta et al., 2011; Wang et al., 2017). However, there has been little research on how the core characteristics of RMS impact on companies' operational performance. The majority of the research that addresses performance issues in RMS has been conducted in the context of case studies and there are few data from empirical investigations using questionnaire-based methodology in the context of RMS (Hollstein et al., 2012; Mehrabi et al., 2002; Spena et al., 2016). These studies have limited empirical focus on the industrial context and offer limited generalisable empirical evidence for the applicability of reconfigurability (Andersen et al., 2017; Bi et al., 2008). They mostly address reconfigurability's characteristics at highly abstract levels and neglect the important differences regarding their implementation in practice (Andersen et al., 2018a). There is a lack of research that must be addressed to provide knowledge on how to assess the current level of reconfigurability, how to implement the core characteristics of reconfigurability and to provide guidelines to improve reconfigurability in either existing or new manufacturing systems. This paper is intended to contribute to this understanding by conducting an exploratory survey that assesses the current level of reconfigurability implementation and its impact on manufacturing systems' operational performance. The results are analysed and discussed through a cluster analysis. An ANOVA analysis is applied to test for statistical differences among the variables related to the complexity, supply chain characteristics and operation performance measures of the manufacturing companies, amongst the clusters identified.

The remainder of this paper is organised as follows: Section 3.2 provides a literature review concerning the core characteristics of reconfigurability, their implementation and their relationship with manufacturing systems' operational performance. Section 3.3 presents the research methodology and the analysis of reliability and validity of the questionnaire. The data collected are presented and discussed in section 3.4. Finally, section 3.5 presents the conclusions, the limitations of this research and suggestions for future studies.

3.2 Literature review

3.2.1 Core characteristics of reconfigurability

To deal with the unpredictability of market requirements and frequent changes induced by technological innovation, manufacturing companies need to be responsive at an affordable cost. To do so, they are required to achieve or implement reconfigurability, which is the ability to repeatedly change and/or rearrange systems' components in a cost-effective way, to meet new environmental and technological changes (Napoleone et al., 2018; Setchi and Lagos, 2004). To achieve the design goals of RMS, manufacturing systems must have the core characteristics implemented that allow them to achieve the system's modularity and scalability required for the production of a part family to meet market demands

(ElMaraghy, 2006; Koren et al., 1999). These core characteristics are the enablers of reconfigurability (Andersen et al., 2018a; Koren, 2006; Mehrabi et al., 2000b).

Six characteristics have been considered the core characteristics of RMS by most authors: customisation, scalability, convertibility, diagnosability, modularity and integrability (Benderbal et al., 2018b; Koren et al., 2018; Wiendahl et al., 2007). Customisation, scalability and convertibility are the vital characteristics for the (natural) system's reconfigurability, while diagnosability, modularity and integrability help to achieve the RMS conversions efficiently in terms of reconfiguration time and effort (Benderbal et al., 2018b; Hasan et al., 2014). A system that possesses these core characteristics has a high level of reconfigurability, which makes reconfigurability a goal in itself (Koren et al., 1999; Koren and Shpitalni, 2010). The core characteristics of reconfigurability are outlined in Table 3.1.

Table 3.1: Core characteristics that enable reconfigurability.

Characteristic	Description	References
Customisation	Manufacturing systems are designed to produce a particular family of parts/products	Koren and Shpitalni (2010)
Convertibility	Transforms existing functionalities of machines, in an operating mode, to suit new production requirements	Koren et al. (1999); Mehrabi et al. (2000a)
Scalability	Throughput capacity can be rapidly and cost-effectively adjusted to abrupt changes in market demand	ElMaraghy (2006); Koren et al. (2016); Wang and Koren (2012)
Diagnosability	Automatically read the current state of a system to detect and diagnose the causes of unacceptable quality of parts and reliability problems	Mehrabi et al. (2000a); Koren and Shpitalni (2010)
Integrability	Ready integration of components and future integration of new technologies	Mehrabi et al. (2000a); Farid (2017)
Modularity	Modular major components to promote their re-use and exchange	Koren and Shpitalni (2010); Benderbal et al. (2018b)

Nevertheless, recent investigation has demonstrated that, convertibility and scalability may merge, because both are directly related to a manufacturing system's responsiveness to sudden changes: convertibility to changes in product mix and scalability to changes in demand (Maganha et al., 2018). Additionally, both characteristics should be considered at the project stage of RMS, which must be designed at the outset for future expansion in its functions and throughput capacity, to enable changes in supply exactly when needed by the market (Koren et al., 2016). Therefore, a more suitable definition that generalises both abilities is adaptability, which can enable manufacturing systems to adapt their capacity and functionality by means of an adjustable structure to changed or new situations (Koren et al., 1999; Maganha et al., 2018). This research is based on the five core characteristics of reconfigurability, as proposed by Maganha et al. (2018): customisation, adaptability, diagnosability, modularity and integrability.

The core characteristics can be implemented in manufacturing systems at different structuring levels, either physical or logical. The physical level includes the core characteristics, while the logical level includes software and control systems (ElMaraghy, 2006). At the physical level, reconfigurability allows changing tools, fixture inspection machines and material handling systems; the layout or the location of the system and machines (Bi et al., 2008; Koren and Shpitalni, 2010). At the logical level, the implementation of reconfigurability facilitates the re-routing, re-planning or capacity planning (ElMaraghy, 2006; Spena et al., 2016). However, various levels of abstraction are involved when considering the actual implementation of reconfigurability in practice. Only a few examples of research explicitly address detailed levels of concretisations of reconfigurability (Andersen et al., 2018a). Hollstein et al. (2012) investigated the relevance and state of implementation of core characteristics of reconfigurability, only at the machine tool level. Spena et al. (2016) conducted a questionnaire survey on small and medium sized companies to investigate the importance of various abstract characteristics of reconfigurability. Andersen et al. (2018a) investigated the core characteristics of reconfigurability in terms of their importance in industry, their current level of implementation in industry, and significant differences in their implementation and criticality across different manufacturing settings. Maganha et al. (2018) empirically investigated the understanding and the current implementation level of reconfigurability in industrial manufacturing companies, testing and validating its core characteristics by using a questionnaire survey. Although these recent studies indicate an advance in approximating theory and practice, there is still insufficient research in several areas, such as i) the selection of the core characteristics of reconfigurability during the system's design, ii) the relationship between the core characteristics and the system's operational performance, iii) the sequence of implementation of the core characteristics, and iv) at which levels, processes and production environments the core characteristics should be implemented. In general, the amount of empirical research on reconfigurability remains limited, without more generalisable evidence (Andersen et al., 2018a). This indicates a need for further investigation on reconfigurability and its core characteristics, and their industrial implementation in different manufacturing environments.

3.2.2 Core characteristics and performance measures

The operational performance of manufacturing systems can be defined in terms of improvements made in plant productivity and a plant's time-based performance (*i.e.* responsiveness) (Schoenherr and Narasimhan, 2012). Traditionally, the operational performance has been measured considering four dimensions: quality, delivery, flexibility and costs (Bortolotti et al., 2015; Hallgren and Olhager, 2009; Singh et al., 2018).

The core characteristics contribute to a company's goals such as low cost and high quality products (Koren, 2013). Efforts have been made to quantify the core characteristics of reconfigurability (Benderbal et al., 2018b; Farid, 2017; Gumasta et al., 2011; Liu et al., 2000). However, most studies to date have investigated the core characteristics of reconfigurability and performance measures separately. Works concerning both issues simultaneously are reduced in number. Maier-Sperredelozzi et al. (2003) proposed metrics for convertibility so that different manufacturing systems can be compared with respect to this area of performance. These metrics are based on assessments of convertibility itself, and on the system's components such as machines and material handling devices, including quality, productivity and responsiveness. Wang and Koren (2012) presented a scalability planning methodology for RMS that can scale the system's capacity incrementally by reconfiguring an existing system, while Koren et al. (2016) proposed a set of principles for system design for scalability to guide designers of modern manufacturing systems. Both studies related scalability to throughput.

The majority of the research addressing the core characteristics of reconfigurability and performance measures has been developed using case studies. This investigation is descriptive and exploratory, attempting to generalise from empirical evidence. This is supported by previous research that suggested the measurement of the impact of the implementation of reconfigurability with respect to the output performance of the factory (Wiendahl et al., 2007).

3.3 Research methodology

The aim of this investigation is to link and analyse the relationship between the core characteristics of reconfigurability and manufacturing systems' operational performance. This paper reports a questionnaire survey that was conducted with Portuguese manufacturing companies to identify the level of implementation of each core characteristic and establish its relationship to operational performance measures, namely quality, delivery, flexibility and costs. The survey research was selected as the appropriate method, because it has been widely applied to gather large amounts of data in relation to a specific research issue, in order to provide generalisable findings (Forza, 2016; Malhotra and Grover, 1998).

3.3.1 Survey design and data collection

This paper uses the scale proposed by Maganha et al. (2018). The questionnaire is composed of three parts. The first part was developed to characterise the respondent companies, in order to understand: the level of complexity of their products, operations and BOM; the extent of the variability in demand or product mix and the objectives and frequency of layout rearrangement. The complexity and supply chain characteristics of the companies surveyed were analysed according to the items referred to in Table 3.2. The second part of the questionnaire concentrated on questions regarding the core characteristics of reconfigurability. All items were measured using a 7-point Likert scale, with the responses ranging from 1 (strongly disagree) to 7 (strongly agree). The third part is composed of questions regarding the operational performance measures of the manufacturing systems: quality, delivery, flexibility and costs. The respondents were asked to compare the performance of their company to their main competitors and these items were also measured using a 7-point Likert scale, with the responses ranging from 1 (low end of industry) to 7 (superior). The questionnaire is presented in the A.

Table 3.2: Complexity and supply chain items used.

Scales	Items	References
Complexity		
of operations	Very few steps/operations required or many steps/operations required	Leachman and Carmon (1992)
of BOM	Very few parts/materials, one-line bill of material or many parts/materials, complex bill of material	Prasad (1998); Helo et al. (2007)
of product	Modular product design or integrated product design	Ericsson and Erixon (1999); Yigit et al. (2002)
Supply chain characteristics		
Changes in product mix	The mix of products you produce changes considerably from week to week	Fisher (1997); Lee (2002)
Variations in supply requirements	Your supply requirements (volume and mix) vary drastically from week to week	
Demand fluctuation	Your demand fluctuates drastically from week to week	
Volume fluctuation	Your total manufacturing volume fluctuates drastically from week to week	
Technical modification of products	Your products are characterised by a lot of technical modifications	
Modifications to parts/components (by suppliers)	Your suppliers frequently need to carry out modifications to the parts/components they deliver to your plant	

Companies were contacted by phone to identify the key respondents and to introduce the objectives of the study (Dillman, 2007). An e-survey was developed, but the access link to the questionnaire was e-mailed exclusively to the target respondents. The main advantages of this data collection method are the lowest relative cost and the ease of securing information. However, an electronic survey usually has lower response rates than other methodologies (Forza, 2016). To ensure a satisfactory response rate a reminder e-mail was sent to urge non-respondents to complete the survey if they had not done so already two weeks after the first contact. Then, two weeks after that reminder, a final appeal was sent to non-respondents. A summary of the survey results was promised to the respondents, evaluating the extent of reconfigurability in their companies.

3.3.2 Characterisation of the sample and response rate

The questionnaire targeted 600 Portuguese manufacturing companies and subsidiaries of multinational companies operating in Portugal, which are currently in operation and have an annual turnover of more than 1 million euros. To construct the sample, the companies were randomly selected from an initial list of 11000 organisations, obtained from the Sabi database (`https://www.bvdinfo.com`). The selection covers manufacturing companies from different industrial manufacturing sectors and are grouped according to their sizes, namely: micro- (<10 employees), small- (10 to 49 employees), medium-sized (50 to 249 employees) and large companies (>250 employees), yielding a heterogeneous sample (European Comission, 2005). This approach was used to ensure a moderate level of external validity and to contribute to the generalisation of the results (Forza, 2016).

From the survey distribution, 7 companies did not respond to the questionnaire, because it was against the companies' policies and 288 did not give any response or justification. In total, 305 responses were received, of which 193 were incomplete, *i.e.* the respondent did not answer all the questions. Consequently, there were 112 usable responses from a population of 600 companies, representing an overall response rate of 18.7%. Table 3.3 summarises detailed data about the composition of the sample and respondents.

Table 3.3: Sample profile.

Characteristic	Frequency	%
Number of employees		
<10	8	7.1
10 to 49	28	25.0
50 to 249	52	46.4
>50	24	21.4
Total	112	100
Respondent's job title		
General manager	31	27.7
Production manager	17	15.2
Quality manager	11	9.8
Factory manager	9	8.0
Process engineer	8	7.1
Industrial manager	7	6.3
Maintenance manager	3	2.7
Other	26	23.2
Total	112	100

3.3.3 Characterisation of production systems and layouts

The respondent companies were also asked about their business production strategies and the type of production layout. The most commonly adopted strategies are summarised in Table 3.4. The majority of the companies surveyed seem to have a high level of customisation, since most of the production strategies applied imply that assembly and manufacturing operations, or even the products' design, only start after receiving firm orders from the customers.

Table 3.4: Business production strategies adopted by companies surveyed.

Business production strategy	%
MTO	51.8
ETO	19.6
ATO	17.0
MTS	11.6

The results, summarised in Table 3.5, show complex operations, BOM and products. The majority of the respondents reported that changes to the product mix, variations in supply requirements and demand fluctuations occur on a weekly basis, while volume fluctuations, technical modifications of products and modifications to parts/components by suppliers are less frequent. These results highlight the need for a highly responsive system, able to respond quickly to sudden market changes.

Table 3.5: Complexity and supply chain characteristics of companies surveyed.

Scales	Mean	SD
Complexity		
of operations	5.02	1.74
of BOM	4.60	1.94
of products	4.17	2.10
Supply chain characteristics		
Changes in product mix	4.36	1.88
Variations in supply requirements	4.20	1.82
Demand fluctuation	4.04	1.80
Volume fluctuation	3.79	1.76
Technical modification of products	3.79	1.82
Modifications to parts/components (by suppliers)	2.90	1.74

The most common layout configuration is the process layout (55.4%), followed by product layout (25.9%) and cellular layout (18.8%). Regarding the frequency of layout rearrangement (Table 3.6), respondents reported that production layout is not modified frequently, *i.e.* the system's structure is predominantly fixed. Moreover, when designing a new layout configuration, the companies surveyed tend to consider the impact that this layout may have on lead time and throughput most frequently, instead of its consequences concerning material handling costs and work in progress inventory levels.

Table 3.6: Frequency and criteria considered when designing a new layout configuration.

Scales	Mean	SD
Frequency		
Layout modification	2.98	1.81
Criteria		
Lead time	5.21	1.57
Throughput	5.16	1.67
Material handling costs	4.45	1.75
Work in progress	4.32	1.70

3.3.4 Reliability and validity analysis

The goodness of measures is evaluated according to reliability and validity. The lack of reliability introduces a random error while the lack of validity introduces a systematic error (Carmines and Zeller, 1979). Reliability refers to the stability and the consistency of the measurement score and indicates dependability, predictability and accuracy, because it refers to the extent to which a measuring procedure achieves the same results in repeated trials (Forza, 2016).

In order to assess the internal consistency of the scales, Cronbach's coefficient alpha α was calculated. The alpha value of 0.7 is often considered the criterion for internal consistency for established scales where an $\alpha \geq 0.8$ indicates that the measure is very reliable. Regarding the internal consistency, the sample size is an important factor, because significance tests were developed for large samples. A sample size of 30 or more is statistically sufficient to calculate the alpha, but it is possible to have more confidence in the accuracy considering large samples (Nunnally and Bernstein, 1994). This study sample of 112 respondents permitted alpha values that ranged from 0.73 to 0.85, which indicates a good level of reliability.

Validity concerns the extent to which the instrument captures what it is intended to capture. The content validity refers to the degree to which the meaning of a set of items represents the domain of the concept under investigation, while the construct validity refers to the degree to which the scores obtained using a set of items behave as expected.

To ensure the construct validity, it is necessary to check the construct's convergent validity and unidimensionality. For this purpose, a confirmatory factor analysis (CFA) was conducted as shown in Table 3.7. The initial measurement with all 25 items resulted in an inadequate fit, thus the model was refined using standard CFA refinement procedures. The items with excessive standardised residuals and modification indices were identified and eliminated one at a time. This refinement was stopped upon attaining generally acceptable model fit thresholds without a substantial reduction in the content validity of constructs. Four items were eliminated from the original 25 items. The fit indices of the refined model met or exceed the minimum threshold values, with a model chi-square (χ^2)>0.05, a root mean square error of approximation (RMSEA)<0.08, a comparative fit index (CFI)>0.9 and a standardised root mean square residual (SRMR)<0.08 (Hu and Bentler, 1999).

Table 3.7: Constructs' validity and reliability.

Items	α	Loading	CR	AVE
Customisation	0.73		0.79	0.57
The location of our equipment on the shop floor was chosen considering the need to produce an entire product family		0.64		
Our manufacturing system's capacity and flexibility (hardware and control system) were designed to match the production needs of a product family		1.00		
Our control system, supported by an open-architecture technology, can be customised to have the exact control functions needed		0.54		
Adaptability	0.82		0.79	0.66
We can easily stop an equipment operation and reconfigure its functions to manufacture a new product type		0.69		
We can change quickly from the manufacturing/assembling one product to another, if they are from the same family		0.85		
Our manufacturing system allows for an easy switch between existing products and can adapt to new/future products		0.82		
Our manufacturing system can easily respond to unexpected equipment failures		0.72		
We can easily add equipment, at any stage of the production process, without interrupting operations for long periods		0.75		
Our throughput can be changed to respond to changes in demand in a relatively short time		0.61		
Diagnosability	0.85		0.85	0.52
Our manufacturing system can automatically detect defective products, diagnose their root causes and reset its parameters to restore the initial situation		0.67		
Our manufacturing system includes inspection resources that allow the detection of quality defects in real time		0.69		
Our manufacturing system uses inspection equipment that can be easily reconfigured for use in different stages of the production process		0.69		
In a start-up phase, we can adjust the manufacturing system parameters, thus reducing the ramp-up time, because we have mechanisms that allow a quick diagnosis of problems with quality		0.75		
Our manufacturing system can automatically identify the source/cause of failures or problems with quality		0.81		
Integrability	0.83		0.84	0.56
We can integrate equipment rapidly and precisely by a set of mechanical, informational and control interfaces in our production system		0.73		
Our equipment is operated/coordinated by an integrated control system, exploited in an open-architecture environment		0.78		
Our manufacturing system allows an easy integration of new equipment and new technologies		0.69		
Our equipment and our control system were designed with interfaces that facilitate the integration of new components		0.80		
Modularity	0.81		0.81	0.59
The major equipment in our manufacturing system can be easily added to, or removed from, the shop floor		0.78		
Our equipment is made of several functional modules that can be easily added/removed		0.83		
The major equipment in our manufacturing system can be easily reorganised to obtain an adapted configuration to manufacture new products		0.68		

From Table 3.7, it is possible to observe that each construct possesses composite reliability (CR)>0.7 and AVE>0.5, above the threshold value suggested for each construct. To establish the constructs' discriminant validity, the squared correlation between two latent constructs was compared to their AVE. Discriminant validity exists if the squared correlation between each pair of constructs is less than the AVE for each individual construct (Forza, 2016). Therefore, it is possible to assume that both convergent and discriminant validity exists.

3.4 Cluster analysis and findings

The data obtained from the respondents were analysed using cluster analysis. The clustering technique is recommended when metric variables are present and the researcher wishes to group entities, based on their similarities of attributes. Therefore, the companies surveyed were classified into a smaller number of mutually exclusive subgroups, based on the implementation level of each core characteristic of reconfigurability. An analysis of the dendogram, that shows the degree of similarity for grouping parts, drove the choice of the number of clusters (Forza, 2016).

Similarity between these entities is commonly expressed in a measure of proximity represented quantitatively by the squared Euclidean distances between pairs of objects based on the set of variables obtained from single- or multi-item scales. The most popular clustering method in operations management is a combination of Ward's hierarchical method and the K-means non-hierarchical method, both of which seek to minimise the sum of the squared Euclidean distances between objects and their cluster centroids (Brusco et al., 2017). This two-step approach, which has been widely supported and recommended in the literature, was used in this research (Steinley and Brusco, 2007). The number of clusters identified was three, which is consistent with $N/60 \leq K \leq N/30$, where N is the number of objects to be clustered and K is the number of clusters (Brusco et al., 2017). The results of the cluster analysis are presented in Table 3.8, Table 3.9 and Table 3.10.

3.4.1 Characterisation of clusters

Cluster 1 is composed of 37 manufacturing companies, among which 54% adopt the MTO business production strategy. These companies belong to the industrial sectors of the manufacture of basic metals, fabricated metal products, machinery and equipment. As shown in Table 3.8, these companies have complex BOM and operations, and present moderate levels of fluctuations in demand, volume or mix of products. In this cluster, there are companies with long product routing, requiring several operations to be accomplished, with a high complex BOM (a great number of parts), which are subject to changes in production volumes and product mix, but to a moderate extent. These companies present the highest

Table 3.8: Complexity and supply chain characteristics in each cluster.

Scales	Cluster 1		Cluster 2		Cluster 3	
	Mean	SD	Mean	SD	Mean	SD
Complexity						
of operations	5.08	1.69	5.07	1.80	4.88	1.75
of BOM	5.16	1.72	4.64	2.01	3.91	1.91
of products	3.95	2.17	4.55	1.98	3.94	2.16
Supply chain characteristics						
Changes in product mix	4.11	1.91	4.62	1.94	4.30	1.78
Variations in supply requirements	3.86	1.80	4.62	1.78	4.03	1.85
Demand fluctuation	3.57	1.74	4.45	1.85	4.03	1.70
Volume fluctuation	3.46	1.82	4.19	1.80	3.64	1.60
Technical modification of products	3.62	1.59	4.24	2.05	3.42	1.70
Modifications to parts/components (by suppliers)	2.51	1.74	3.31	1.79	2.82	1.61

Table 3.9: Frequency of changes in layout configuration in each cluster.

Scale	Cluster 1		Cluster 2		Cluster 3	
	Mean	SD	Mean	SD	Mean	SD
Layout modification	2.89	1.82	3.45	2.02	2.48	1.37

Table 3.10: Current implementation level of the core characteristics in each cluster.

Characteristic	Cluster 1		Cluster 2		Cluster 3	
	Mean	SD	Mean	SD	Mean	SD
Customisation	5.45	0.58	4.88	1.14	4.08	0.88
Adaptability	5.27	0.67	4.87	0.92	3.71	0.79
Diagnosability	4.24	1.20	4.19	1.18	3.33	1.30
Integrability	3.65	1.08	4.39	1.06	2.65	0.88
Modularity	2.35	0.84	4.64	0.77	2.33	0.83

implementation levels of customisation and adaptability. The customisation, in this case, is not related to the variability, but to the design of the manufacturing system around a product family. The complexity of BOM and the modular design of their products, may imply that these companies manufacture a set of similar products, composed of standard components. Consequently, the number of products or family of products is limited. Moreover, although there are fluctuations in product mix, they seem to be insignificant. Thus, these companies present a high level of adaptability implemented, because they do not need to perform drastic modifications when changing from one product to another. In fact, the transition from one product to another seems to be relatively easy. Customisation and adaptability are the vital characteristics for the (natural) system's reconfigurability, but they do not make RMS conversions efficient in terms of reconfiguration time and effort (Benderbal et al., 2018b; Hasan et al., 2014). Nevertheless, they might contribute to the reduction of reconfiguration costs (Koren et al., 1999).

Cluster 2 includes 42 companies, mainly from the sector of the manufacture of motor vehicles, trailers and semi-trailers, and electrical equipment. 57% of them adopt the MTO business production strategy and are subjected to weekly changes in demand, volume and product mix, which implies frequent changes in supply requirements. Companies within this second cluster mostly adopt product layouts (26%) and manufacturing cells (26%) and reported frequent technical modification of products, which implies modifications of parts/components by the suppliers. In cluster 2, there are companies that manufacture products with an integrated design, but with a simpler BOM (lower number of parts), which face moderate to high levels of variability in terms of demand, volumes and product mix. Thus, these companies seem to be characterised by the flow shop production type. Customisation is essential for companies that adopt the make-to-order production strategy, to cope with the variability. Nevertheless, in this case, designing the manufacturing system around a product family may not be the most convenient approach, given the integrated design of products. In addition, they are subjected to the highest levels of variability in product mix and volume, which implies changes in the layout configuration several times a year (Table 3.9). This is why these companies present the highest levels of integrability and modularity implemented. Modularity and integrability are supporting characteristics that help achieve RMS conversions efficiently in terms of reconfiguration time and effort, when adapting existing manufacturing systems to new situations (Hasan et al., 2014). Both characteristics permit rapid reconfiguration, but they do not guarantee modifications in production capacity and functionality (Koren and Shpitalni, 2010).

Furthermore, clusters 1 and 2 present high levels of diagnosability implemented. Despite the difference between means, an ANOVA test for post-hoc confidence interval of 95% demonstrated that there is no significant difference between cluster 1 and 2 concerning this core characteristic. As modularity and integrabitility, diagnosability might facilitate a rapid reconfiguration, therefore reducing reconfiguration time and effort (Koren and Shpitalni, 2010; Hasan et al., 2014). For companies in cluster 1 that face low variability in demand, this characteristic represents the design of the manufacturing system for easy diagnosis. These companies can identify and diagnose the main causes of product defects and correct the operational deficiency quickly (Benderbal et al., 2015). On the other hand, for companies in cluster 2, that face high variability in demand, it is important to have low ramp up times when promoting changes to cope with fluctuations in product mix or volumes, because stopping a line or cell implies stopping the production of a whole product family. Diagnosability assumes a great importance in this case, because it refers to the ability to read the state of the system and obtain information on which corrections have to be carried out in order to reach the planned performance, which is particularly important in the ramp up phase after each reconfiguration (Andersen et al., 2017).

Cluster 3 includes 33 manufacturing companies. Generally, they are from the sector of manufacturing of food, rubber and plastic products. These companies have the simplest products, BOM or operations, but they are subject to moderate levels of variability in terms of demand, volume or product mix. In the third cluster, there are companies that manufacture simple products, with short product routing, requiring few operations to be performed, with a simple BOM (small number of parts), which, such as companies in cluster 1, are subject to moderate levels of variability. Having simple products, BOM and operations, implies that manufacturing processes are designed to produce a stable mix of products and to respond to a stable demand. This is confirmed in Table 3.9, which shows that companies within this cluster presented the lowest frequency of layout modifications. Companies with a stable product mix and production volumes, that manufacture modular products with simple BOM and routing, do not need to embrace reconfigurability improvement projects, because they prioritise high throughput rates, thus, productivity. Indeed, it is expected that companies subject to lower levels of variability have a lower level of reconfigurability implemented in their manufacturing systems. This is the reason why layouts or manufacturing processes are not re-designed frequently. The third cluster contains the greatest number of companies that adopt the MTS business production strategy (42%) and, consequently, do not need high levels of reconfigurability implemented. These are essentially process manufacturing companies, in which reconfigurability seems to be less important. Therefore, companies within cluster 3 present the lowest levels of all the core characteristics implemented, because it is not an advantage for them.

The implementation level of each core characteristic in each cluster is summarised in Table 11. This level was classified accordingly to the following scale: none (1.00 to 2.00), very low (2.01 to 3.00), low (3.01 to 4.00), moderate (4.01 to 5.00), high (5.01 to 6.00) and very high (6.01 to 7.00).

Table 3.11: Summary of manufacturing systems' performance measures.

Cluster	Industrial sector	Customisation	Adaptability	Diagnosability	Integrability	Modularity
Cluster 1	Basic metals, fabricated metal products, machinery and equipment	High	High	Moderate	Low	Very low
Cluster 2	Motor vehicles, trailers and semi-trailers, and electrical equipment	Moderate	Moderate	Moderate	Moderate	Moderate
Cluster 3	Foods, rubber and plastic	Moderate	Low	Low	Very low	Very low

As shown in Table 3.11, the core characteristics of reconfigurability seem to be moderately implemented in each cluster of the companies surveyed. The clusters present moderate to high levels of customisation implemented, as well as moderate to high levels of adaptability (convertibility and scalability). Therefore, these seem to be the most implemented core characteristics of reconfigurability. These findings are aligned with the findings of Spena et al. (2016) and Andersen et al. (2018a), who demonstrated that dimensioning and designing manufacturing for different technological and processing requirements is perceived as being critical in industry. Likewise, in previous research, environments dominated by make-to-stock production require more static and physical changes of production capacity, while more MTO production environments tend to require dynamic or logical scalability actions with a very short time horizon. In addition to that, the need for/implementation of reconfigurability in manufacturing systems depends not only on the level of variability to which they are subjected, but also on the type and the complexity of products manufactured (modular or integrated product design), BOM and operations and the routing characteristics present in their manufacturing systems. This is one of the most important contributions of this paper and that has not been identified in the literature yet.

3.4.2 Operational performance measures

To investigate the impact of reconfigurability on manufacturing systems' operational performance, the implementation level of the core characteristics was compared to the operational performance measures in each cluster. As mentioned before, this analysis was conducted considering the four operational performance measures traditionally reported in the literature: quality, delivery, flexibility and cost. Quality was measured by the conformance to product specification; delivery was measured by on time delivery and fast delivery; flexibility was measured by the flexibility to change volume and product mix; and cost was measured by the unit cost of manufacturing (Bortolotti et al., 2015; Hallgren and Olhager, 2009; Schoenherr and Narasimhan, 2012; Singh et al., 2018). Respondents were asked to compare the performance of their company to their main competitors. The results are shown in Table 3.12, in which the last column highlights the p-values obtained from the ANOVA test, considering a 0,05 level of significance.

Table 3.12: Current manufacturing systems' operational performance measures.

Operational performance	Cluster 1		Cluster 2		Cluster 3		ANOVA
	Mean	SD	Mean	SD	Mean	SD	p-value
Conformance to product specification	5.24	1.12	5.02	1.05	4.17	1.05	**0.00**
On time delivery	4.78	1.06	4.90	1.12	4.76	1.00	0.82
Fast delivery	5.11	1.24	5.12	1.23	4.97	1.16	0.85
Flexibility to volume change	3.46	1.80	4.89	1.80	3.64	1.59	**0.00**
Flexibility to product mix change	4.11	1.91	4.62	1.94	4.30	1.78	0.48
Unit cost of manufacturing	4.32	1.13	4.45	1.13	4.30	1.08	0.81

In Table 3.13, the current operational performance in the companies surveyed are classified according to the same criteria used in Table 3.11.

Companies in clusters 1 and 2 reported better quality performance than companies from cluster 3. Both clusters also presented the highest levels of diagnosability implemented. This leads to the conclusion that the implementation level of diagnosability may impact positively on the quality performance of manufacturing systems. As production systems

Table 3.13: Summary of manufacturing systems' operational performance measures.

Cluster	Conformance to product specification	On time delivery	Fast delivery	Flexibility to volume change	Flexibility to volume change	Unit cost of manufacturing
Cluster 1	High	Moderate	High	Low	Moderate	Moderate
Cluster 2	High	Moderate	High	Moderate	Moderate	Moderate
Cluster 3	Moderate	Moderate	Moderate/ High	Low	Moderate	Moderate

are made more reconfigurable and their functionality and layouts are modified more frequently, it becomes essential to tune the newly reconfigured system rapidly so that it can produce quality parts quickly (Koren et al., 1999). Diagnosability enables rapid ramp-up and the production of good quality products (Koren, 2013). Companies within these clusters are capable of identifying the sources of quality and reliability problems quickly, automatically reading the current state of the system to detect and diagnose the root causes of output product defects, and correcting operational defects quickly, thus improving the conformance to product specification. In practice, performing in-process diagnostics has a double advantage: it dramatically shortens the ramp-up periods after reconfigurations and it allows rapid identification of problems with the quality of parts during normal production (Koren and Shpitalni, 2010).

On the other hand, companies in cluster 2 show better performance than clusters 1 and 3 in terms of flexibility. This may occur due to the levels of integrability and modularity implemented. Although diagnosability allows a rapid reconfiguration of manufacturing systems, this characteristic by itself is not enough to reconfigure a manufacturing system quickly, which may impact on its operational performance (Koren and Shpitalni, 2010). However, diagnosability combined with modularity and integrability, supports RMS in achieving conversions efficiently in terms of reconfiguration time and effort (Koren et al., 1999). Modularity promotes the quick introduction of new technologies and encourages a more flexible allocation of production facilities both locally and globally (Benderbal et al., 2018b). Integrability influences the speed of the replacement of the modules in a manufacturing system and allows the integration of modules rapidly and precisely, in order to benefit modularity (Napoleone et al., 2018). Moreover, with highly flexible resources and know-how for specific technologies, companies can be quite adaptable to product and volume changes, thus improving the manufacturing system's flexibility and contributing to the reduction of reconfiguration time and cost. Due to the presence of known and tested modular parts (of a manufacturing system), the required configuration time and resources are reduced (Puik et al., 2017).

Adaptability is the core characteristic that allows a quick changeover between products and quick adaptability for future products, by transforming systems' functionality and incrementally changing capacity rapidly and economically, by adding or subtracting manufacturing resources and/or changing components of the system (ElMaraghy, 2006). Therefore, it is expected that companies that show higher levels of adaptability implemented also show a greater ability to change production volume and product mix (*i.e.*, flexibility). Nevertheless, companies in the first cluster, that have the highest levels of adaptability implemented, reported worse performance in terms of flexibility to volume change than companies in the second cluster, that have the highest levels of integrability and modularity implemented. The analysis of this empirical evidence may lead to two viable conclusions. As companies within cluster 1 face the lowest levels of fluctuations in demand, the first possible conclusion is that these companies do not need to change production volume; therefore, they do not need a higher performance in flexibility. This may also explain why companies in cluster 3 reported better performance in terms of flexibility than companies in cluster 1; companies in the third cluster are subject to moderate levels of variability in terms of demand, volume or product mix. Indeed, regarding the operational performance, the results support the idea that companies from cluster 1, which prioritise the implementation of customisation and adaptability, behave almost in the same manner as companies from cluster 3, which are mostly process manufacturing companies that do not need to implement reconfigurability. Therefore, implementing only customisation and adaptability does not guarantee a level of reconfigurability that might impact on the operational performance of the manufacturing system in terms of quality, delivery, flexibility and costs.

The second possible conclusion is that manufacturing systems that show high levels of implemented adaptability, but lack the implementation of integrability and modularity, which are the characteristics that allow for a rapid reconfiguration, cannot achieve a high performance in terms of flexibility. Flexibility is achieved by the ability and potential of the manufacturing system to perform quick adjustments in its functionality and capacity, at operational and strategic levels, to meet the demands of customers (Marks et al., 2018). However, the presence of modularity and integrability should impact on adaptability (Napoleone et al., 2018). This is supported by the results of the companies in cluster 2, which have the highest levels of integrability and modularity implemented and presented better performance in terms of flexibility. Moreover, these findings are aligned with Napoleone et al. (2018), who established a sequence for the implementation of the core characteristics of reconfigurability. According to these authors, modularity and integrability are basic core characteristics that should be considered and implemented in the configuration stage of the manufacturing system, which are then followed by the implementation of diagnosability. Following this, the implementation of adaptability, that is a reconfiguration characteristic, should impact on the implementation of the last core characteristic, which is customisation. Thus, considering the impact of the core characteristics on the operational performance, this sequence of implementation might provide better results.

Costs, *i.e.* the unit cost of manufacturing, does not seem to be affected by the level of the core characteristics of reconfigurability implemented, although some authors argue that the manufacturing costs can be reduced by using a modular production system that shortens the change time as well as reduce the expenses for planning (Benderbal et al., 2018b). The implementation of reconfigurability also seems not to influence on time delivery. The ANOVA test performed confirmed that there is no significant statistical difference between these performance measures among the three clusters. Nevertheless, in terms of fast delivery, although the ANOVA test revealed that there is not a significant statistical difference between the results of cluster 2 and 3, the difference between means could lead to the conclusion that companies within cluster 2 present a better performance for fast delivery than cluster 3. This is supported by Wiendahl et al. (2007) that argues that, with the orientation of manufacturing systems for customers' needs (customisation), integrability and modularity provide a means to (re)structure RMS by targeting the added value for customers through fast deliveries. Therefore, this leads to a relationship between customisation, integrability, modularity and the measure for delivery performance, but only in terms of fast delivery.

In short, our findings support the premise that the implementation level of the core characteristics might have an impact on the operational performance of manufacturing systems. The main findings, the core characteristics and the operational performance measures impacted on are summarised in Table 3.14.

Table 3.14: Summary of the main findings, the core characteristics and the operational performance measures impacted on.

Characteristic	Main findings	Operational performance
Customisation	The design of a manufacturing system around a part/product family guides the system for customers' needs. The implementation of customisation combined to integrability and modularity might contribute to fast deliveries.	(fast) Delivery
Adaptability	The adaptability provides the ability to cope with demand variability, in terms of volume and product mix. The implementation of adaptability together with modularity and integrability might contribute to better results in the manufacturing systems' operational performance.	Flexibility
Diagnosability	It allows the detection of quality and reliability problems, the diagnoses of root causes of defective products and the correction of operational defects.	Quality
Integrability/Modularity	These characteristics enable a rapid reconfiguration of the manufacturing system, in terms of time and effort. The implementation of modularity and integrability should impact on the implementation of adaptability. If combined with flexible and standardised resources, these characteristics might have a greater impact on the operational performance.	Delivery/Flexibility

3.5 Conclusion and further research

Although RMS have been discussed over the last decades, there is very little evidence of empirical research concerning the core characteristics of reconfigurability and operational performance measures (Andersen et al., 2018a; Wiendahl et al., 2007). This study focuses on an empirical analysis of reconfigurability and its impact on manufacturing systems' operational performance. Four performance indicators were measured: quality, delivery, flexibility and cost. The analysis was conducted using survey research, seeking to generalise from empirical evidence. The questionnaire was applied to 600 Portuguese manufacturing companies and 112 usable responses were obtained, representing a response rate of 18.7%. The reliability and validity achieved provide tentative evidence that this measurement instrument is reliable and valid. Reliability was demonstrated with Cronbach's alpha values, which all exceeded 0.7 and four of them (adaptability, diagnosability, modularity and integrability) obtained Cronbach's alpha values of ≥ 0.8, thereby indicating very reliable measures.

The findings support the idea that the core characteristics of reconfigurability impact on the operational performance of manufacturing systems. Furthermore, these characteristics can contribute to a reduction in the time and effort of reconfiguration, and consequently enhance a system's responsiveness. These characteristics can reduce lifetime cost reliably by enabling a system to change constantly during its lifetime, responding to changes in markets, consumer demand and process technology (Koren and Shpitalni, 2010).

In addition, it has been possible to assess the implementation level of each core characteristic in the companies surveyed in each cluster throughout this investigation. Customisation is the most implemented characteristic, while modularity is the least. In contrast with recent research (Andersen et al., 2018a), this might indicate that customisation is the easiest characteristic to implement, while modularity is the hardest, but this does not mean that modularity is the least critical. Actually, the results indicate that modularity, as well as integrability, might impact on two out of the four performance measures analysed, therefore identifying critical core characteristics to implement in manufacturing systems. These two characteristics combined with adaptability seem to significantly improve the flexibility of the system. On the other hand, the implementation of customisation and adaptability by themselves, does not guarantee a level of reconfigurability that could impact on the operational performance of the manufacturing system.

The impact on operational performance is not only a matter of which of the core characteristics are implemented in manufacturing systems, but also of the production environment, the responsiveness required and the dependency that exists among the characteristics. In fact, the cluster analysis demonstrates that the need/implementation of reconfigurability in manufacturing systems depends not only on the level of variability to which they are subjected, but also on the type and the complexity of the characteristics of the products and routings present in the manufacturing systems. For instance, a high level of reconfigurability is not required, nor desirable, for companies functioning in stable markets. In this case, other strategies must be pursued to improve manufacturing performance. Nevertheless, companies that are facing more turbulent environments require an increase in the level of reconfigurability of their manufacturing systems.

In practical terms, the questionnaire developed can be used by managers to assess the degree of reconfigurability of their production systems and for internal and external benchmarking. Knowing the level of implementation of each core characteristic and how each one can be improved might help managers to decide strategies to increase the reconfigurability of their production systems and improve their operational performance. In addition to that, the main findings of this work, summarised in Table 3.14, may serve as a guide for managers to address specific issues regarding the reconfigurability of their manufacturing systems. This knowledge could be used and applied by industrial stakeholders to improve their manufacturing systems, according to the required degree of reconfigurability, and to identify the core characteristics that should be implemented for their specific industrial scenario.

This investigation presents a greater sample size and covers a wider range of industrial sections than previous research (Andersen et al., 2018a; Spena et al., 2016). Nevertheless, the data for this survey were collected from companies based in Portugal. Therefore, the replication of this questionnaire in other countries is recommended for future research in order to confirm its findings. Other directions for further studies concern the use of this research instrument to validate conceptual frameworks that establish the relationship and the order of implementation of the core characteristics. The proposed questionnaire could also be the basis for the development of an index to measure reconfigurability. Future research should be directed at the core characteristics of reconfigurability that seem to be implemented to a lesser extent in manufacturing companies, seeking to identify solutions to improve their level of implementation. Other methodologies, *e.g.* case studies, should also be considered for an in-depth analysis of the impact of reconfigurability on the operational performance of manufacturing systems. Finally, it would be interesting to understand how the core characteristics interact (*e.g.*, whether they possess similar/different behaviour or whether one impacts positively/negatively on another).

Chapter 4 An analysis of reconfigurability in different business production strategies

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Abstract

Reconfigurability is the ability to rearrange manufacturing systems' components to deal with product variety and fluctuations in demand. It has various core characteristics that can be designed in many different ways to provide to the manufacturing systems the appropriated abilities to cope with these changes. This chapter is intended to conduct an exploratory analysis of the implementation of reconfigurability in companies using different business production strategies, namely make-to-order, engineer-to-order, assembly-to-order and make-to-stock. To achieve this objective, an aggregated measure of reconfigurability is used. This measure can be useful to understand the needs of reconfigurability in manufacturing companies using different production strategies. This study uses a questionnaire-based methodology. The findings suggest that the levels of implementation of reconfigurability are different among companies adopting different production strategies This occurs because different production strategies are associated to different levels of variations in product mix and, consequently, different needs of reconfigurability. This chapter also presents some guidelines to improve the levels of reconfigurability implemented, considering the particularities of each production strategy analysed.

4.1 Introduction

Manufacturing systems must be responsive to abrupt changes in demand volume and product mix. RMS play a key role in responding to the current challenges faced by industries, because they can provide rapid changes in structure to adjust the production capacity and functionality in response to sudden changes in manufacturing requirements (Koren et al., 1999).

Reconfigurability has been widely studied in the literature referred to RMS (Napoleone et al., 2018). It can be implemented at the levels of equipment, manufacturing and systems to efficiently and dynamically change the functionality and capacity boundaries of the system, with limited effort (Koren et al., 1999; Andersen et al., 2018a). At an operational/tactical level, reconfigurability can be seen as the ability to rearrange manufacturing elements in order to adjust to new environmental and technological changes and, at a tactical/strategic level, as an engineering characteristic that deals with the design of machines and systems for customised products in a cost effective market (Maganha et al., 2018).

Implementing reconfigurability to accommodate product variety, customisation, small batch sizes, fluctuating market demand and the frequent introduction of new products can provide capacity and functionality on demand, thereby reducing the trade-off between productivity and flexibility (Koren and Shpitalni, 2010). However, approaching reconfigurability as an absolute feature of a manufacturing system is inadequate, as it has various different characteristics that can be designed in unlimited ways to provide context-specific and the appropriate ability to cope with changes (Andersen et al., 2018a).

Reconfigurability can be achieved when the manufacturing systems possesses some core characteristics implemented, that can increase their speed of responsiveness when faced with unpredicted events (Bruccoleri et al., 2005). This makes reconfigurability a goal in itself (Koren and Shpitalni, 2010; Koren et al., 1999). For this reason, knowing the core characteristics of reconfigurability is of foremost importance for manufacturing companies (Gumasta et al., 2011).

Previous works have measured the reconfigurability of RMS (Farid, 2017; Gumasta et al., 2011; Wang et al., 2017) and have studied empirically the reconfigurability implemented in manufacturing systems (Andersen et al., 2018a; Spena et al., 2016). However, research concerning the analysis of which core characteristics of reconfigurability are required in different manufacturing environments is limited. The objective of this chapter is to conduct an exploratory analysis of the implementation of reconfigurability, considering different business production strategies, using a questionnaire-based methodology. To do so, an aggregated measure, adapted from Anderson and Fornell (2000), is used to assess the reconfigurability through its core characteristics. This aggregated measure can be useful to understand the current level of reconfigurability in manufacturing companies, that act under different business production strategies, specifically MTS, MTO, ATO and ETO. This analysis will allow to understand whether the level of reconfigurability present in the companies surveyed depends on their production strategy. This, in turn, will permit the definition of some guidelines to improve the levels of implementation of reconfigurability, taking into account the particularities of each type of production strategy.

4.2 Literature review

Reconfigurability is the ability to repeatedly change or rearrange manufacturing systems' components, in a cost-effective way, to better cope with high product variety and fluctuations in market demand (Setchi and Lagos, 2004). To enable reconfigurability, manufacturing systems must have some core characteristics implemented, such as modularity, integrability, customisation, adaptability and diagnosability (Maganha et al., 2018).

Modularity promotes the exchange and re-use of systems' components and helps in the quick introduction of new technologies (Benderbal et al., 2018b). Integrability is the ability with which systems and components may be readily integrated (Farid, 2017). Customisation refers to the selection of tools and components based on the need of manufacturing a product family (Wang et al., 2017). Adaptability is the property of manufacturing systems that enable them to adapt their capacity and functionality by means of an adjustable structure (Maganha et al., 2018). Diagnosability is the capacity to detect and diagnose the main causes of a product defect and correct operational deficiencies rapidly (Liu et al., 2000).

Knowledge regarding the importance of the core characteristics in different manufacturing environments is valuable when designing reconfigurable solutions in industry, where they are selected and implemented in accordance with the specific requirements of the manufacturing company (Andersen et al., 2018a).

To deal with the challenges promoted by Industry 4.0 paradigm, manufacturing companies need to understand the various enablers of reconfigurability (Gumasta et al., 2011). Previous studies have quantified some of the core characteristics of reconfigurability (Benderbal et al., 2018b; Liu et al., 2000; Maier-Sperredelozzi et al., 2003). Nevertheless, to assess the reconfigurability implemented in manufacturing systems, its core characteristics must be measured together. Approaching the core characteristics in isolation or assessing the reconfigurability as a universal concept is inadequate, because the enablers of reconfigurability can be designed in many ways to provide the appropriated abilities to cope with abrupt changes in production requirements (Andersen et al., 2018b).

Taking this into account, Gumasta et al. (2011) have developed an index to measure reconfigurability considering modularity, scalability, convertibility and diagnosability. These core characteristics have been mapped together using multi-attribute utility theory. A reconfigurability measurement process based upon axiomatic design knowledge base and the design structure matrix has been developed by Puik et al. (2013). Farid (2017) have discussed how integrability, convertibility and customisation fit the requirements for reconfigurability measures in manufacturing systems. Wang et al. (2017) have proposed an evaluation index that reflect six characteristics of reconfigurability, specifically scalability, convertibility, diagnosability, modularity, integrability and customisation, based on the preference ranking organisation method for enrichment evaluation (PROMETHEE).

Previous empirical research that assessed the level of reconfigurability implemented in manufacturing systems, have considered its importance in regard to changes in volume and product mix, and to the introduction of new products (Andersen et al., 2018a). However, the amount of empirical research concerning the analysis of which core characteristics of reconfigurability are required in different manufacturing environments is limited. For this reason, this chapter is intended to analyse the level of reconfigurability, by comparing its implementation in different manufacturing environments, according to the type of business production strategy. To achieve this objective, this study uses an aggregated measure of reconfigurability, adapted from Anderson and Fornell (2000), that considers five core characteristics: modularity, integrability, customisation, adaptability and diagnosability (Maganha et al., 2018). This study is based on empirical evidence obtained from a questionnaire survey that was conducted with Portuguese manufacturing companies.

4.3 Research method

Based on the reviews of the RMS literature and academic experts, a survey was conducted to assess the different core characteristics of reconfigurability. The survey is based on the scales proposed by Maganha et al. (2018). To facilitate greater data accuracy and faster response times, the electronic process of designing the survey was adopted (Forza, 2016). An electronic survey was developed, but companies were contact by phone to identify the key respondents and to introduce the objectives of the study (Dillman, 2007). To guarantee a satisfactory response rate, a reminder e-mail was sent to urge non-respondents to complete the survey if they had not done so, already two weeks after the first contact. Then, two weeks after that reminder, a final appeal was sent to non-respondents.

The survey was applied to 600 Portuguese companies. From the survey distribution, 305 responses were received, of which 193 were incomplete. Therefore, there were 112 usable responses, representing a response rate of 18.7%.

Companies of different sizes and different industrial sectors were selected in order to obtain a heterogeneous sample. This approach was used to ensure a moderate level of external validity and to contribute to the generalisation of the results (Forza, 2016). The selection covers manufacturing companies from different industrial sectors and which are grouped according to their sizes: 7% of micro (<10 employees), 25% of small (10 to 49 employees), 46% of medium (50 to 249 employees) and 21% of large companies (>250 employees) (European Comission, 2005). The preferred target respondents were the managers with direct involvement in operational/strategic decisions and knowledge of production processes: general manager (28%), production manager (15%), quality manager (10%), factory manager (8%), process engineer (7%), industrial manager (6%) maintenance manager (3%) and others (23%).

The companies surveyed were also asked about their business production strategy. The most common are MTO (52%), ETO (20%), ATO (17%) and MTS (12%). Thereby, the majority of the companies surveyed seem to have a high level of product customisation, because most of the production strategies adopted imply that assembly, operations or even the products' design, can only start after receiving firm orders from the customers. Therefore, in this chapter, an exploratory analysis is conducted, by comparing the aggregated measure of reconfigurability proposed in different manufacturing environments, grouped according to the type of the production strategy: MTO, ETO, ATO and MTS.

4.3.1 Data analysis

The goodness of measures is evaluated according to reliability and validity (Forza, 2016). In order to assess the reliability of the scales, Cronbach's coefficient alpha (α) was calculated. The alpha value of 0.7 is often considered the criterion for internal consistency for established scales where an $\alpha \geq 0.8$ indicates that the measure is very reliable (Nunnally and Bernstein, 1994). To ensure the construct validity, a CFA was conducted. The model was refined using standard CFA refinement procedures. The items with excessive standardised residuals and modification indices were identified and eliminated one at a time. This refinement was stopped upon attaining generally acceptable model fit thresholds without a substantial reduction in the content validity of constructs. The fit indices of the refined model met or exceed the minimum threshold values, with a model χ^2 >0.05, a RMSEA<0.08, a CFI>0.9 and a SRMR<0.08 (Hu and Bentler, 1999).

In Table 4.1, each construct possesses a CR>0.7 and an AVE>0.5, both above the threshold value suggested for each construct. To establish constructs' discriminant validity, the squared correlation between two latent constructs was compared to their AVE. Discriminant validity exists if the squared correlation between each pair of constructs is less than the AVE for each individual construct (Forza, 2016). As shown in Table 4.2, all AVE values are greater than the square root of correlations among the constructs. Therefore, it is possible to assume that both convergent and discriminant validity exists.

Table 4.1: Constructs' reliability and validity.

Construct	Items	α	CR	AVE
Modularity	3	0.81	0.81	0.59
Integrability	4	0.83	0.84	0.56
Customisation	3	0.73	0.79	0.57
Adaptability	6	0.82	0.79	0.66
Diagnosability	5	0.85	0.85	0.52

Table 4.2: AVE of constructs and the squared correlation.

Construct	Modularity	Integrability	Customisation	Adaptability	Diagnosability
Modularity	*0.769*				
Integrability	0.421	*0.748*			
Customisation	0.014	0.277	*0.752*		
Adaptability	0.165	0.353	0.356	*0.812*	
Diagnosability	0.188	0.390	0.065	0.184	*0.723*

4.3.2 Aggregated measure of reconfigurability

To measure the reconfigurability (R) of companies using each type of business production strategy, the formula proposed by Anderson and Fornell (2000) was used, as in Equation 4.1.

$$R = \left(\frac{\sum_{i=1}^{N} w_i \bar{x}_i - \sum_{i=1}^{N} w_i}{n \sum_{i=1}^{N} w_i} \right) \cdot 100 \tag{4.1}$$

In this formula, w_i is the weight measurement of item i, $\bar{x}_i$ is the average measurement value of item i, and n is the number of items. In this case, $n = 5$, since five core characteristics of reconfigurability are considered. The characteristics are assumed to have equal weights.

4.4 Results

The levels of implementation of reconfigurability, according to the business production strategy adopted, are presented in Table 4.3. An ANOVA test for post-hoc confidence interval of 95% was performed to establish the statistical difference among the core characteristics.

Table 4.3: The implementation of reconfigurability, according to the production system adopted.

Construct	MTO		ETO		ATO		MTS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Modularity	3.53	1.22	2.92	1.23	2.82	1.14	2.61	1.16
Integrability	3.72	1.09	3.66	1.36	3.71	1.45	3.08	0.84
Customisation	5.08	0.94	4.73	1.10	4.47	1.05	4.44	1.20
Adaptability	4.70	0.99	4.73	1.20	4.61	0.90	3.92	1.03
Diagnosability	4.08	1.25	3.65	1.16	3.92	1.24	4.42	1.65

The aggregated measure of reconfigurability calculated for the companies acting under an MTO business production strategy is presented in Table 4.4. The same procedure was used for the remaining production strategies. The following values were obtained: 58.76 for ETO, 58.12 for ATO and 53.88 for MTS.

Table 4.4: The aggregated measure of reconfigurability in MTO production systems.

Construct	w_i	$\bar{x}_i$	$\sum w_i$	$w_i\bar{x}_i$	$\sum w_i\bar{x}_i$	Value
Modularity	0.20	3.53	1.00	0.71	4.22	64.44
Integrability	0.20	3.72		0.74		
Customisation	0.20	5.08		1.02		
Adaptability	0.20	4.70		0.94		
Diagnosability	0.20	4.08		0.82		

4.5 Discussion

The objective of this chapter is to conduct an exploratory analysis by comparing the aggregated measure of reconfigurability of different manufacturing environments. This aggregated measure was calculated based on five core characteristics: modularity, integrability, customisation, adaptability and diagnosability.

Companies using the MTO production strategy present the highest value (64.44) of the aggregated measure of reconfigurability. Thus, they have the highest levels of implementation of reconfigurability. This can be explained because these companies typically produce in small batches, being subjected to a high level of variability in the product mix and demand volume. Next, with similar values of the aggregate measure of reconfigurability appears the ATO and ETO production strategies (58.12 and 58.76, respectively). These values were not expected, especially for ETO companies that typically are associated to the production of one-of-a-kind products. For this type of companies, it is expected that the variability in the product mix will be higher than in companies with MTO production strategies. Thus, for them, reconfigurability should be, at least, as much important as for MTO companies. Nevertheless, they present a lower level of implementation of reconfigurability. Therefore, these lower values are presented by ATO and ETO companies, not because they need smaller levels of reconfigurability, but probably because in these types of production strategies reconfigurability is more difficult to implement. They would benefit if they had higher level of reconfigurability implemented. MTS production systems presented the lowest value of the aggregated measure of reconfigurability (53.88). The majority of MTS companies belongs to the sector of food products manufacturing. For them, reconfigurability seems to be less important, because they act in stable markets, with low variability in product mix.

In MTO production systems, where the manufacturing operations only start after receiving the customers' orders, customisation was ranked first. The majority of these companies belong to the industrial sectors of the manufacture of motor vehicles, trailers and semi-trailers. They manufacture products with a great number of parts that require several operations to be accomplished. For them, customisation is essential to manufacture a product. Adaptability was ranked second. It is essential in this type of production system that face high variability in demand volume and product mix. It allows the adjustment of their function and capacity in order to respond to abrupt changes in production requirements. The characteristic ranked third was diagnosability. It is important to MTO systems to promote low ramp up times after each reconfiguration. Indeed, it provides a rapid reconfiguration of the manufacturing system, thus reducing reconfiguration time and effort (Koren and Shpitalni, 2010). Integrability and modularity were the least ranked characteristics. Manufacturing companies seem to face difficulties to integrate control systems and cope with the introduction of new equipment and/or new technology. Consequently, the lack of interfaces increase the barriers that impede the implementation of modularity (Koren et al., 1999). MTO production systems can benefit from the technological advances of the Industry 4.0 paradigm to improve the level of implementation of these two characteristics. For example, the use of sensors, compatible information systems, reconfigurable controls, lightweight equipment and mobile/collaborative resources might facilitate the collection and transmission of real data and an easy addition to or removal of resources (Maganha et al., 2018).

The levels of implementation of each core characteristic of reconfigurability in ATO and ETO are very similar. Indeed, the ANOVA test did not show any significant statistical difference between the averages. For this reason, they will be discussed together, using the term A/ETO. The ranking of the core characteristics in A/ETO is similar to that of MTO production systems. However, there are significant differences among the averages of modularity, customisation and diagnosability for these two types of production strategies. Thus, it can be concluded that modularity, customisation and diagnosability are less present in A/ETO companies than in MTO companies. In A/ETO the products are assembled or designed and manufactured following specific customers' orders. They assume a higher variability in the product mix and a variability in demand volume at least similar to MTO environments. In ETO, for instance, each product is different from all the others already produced. Many different tools and/or equipment might be required to manufacture a product. It is difficult to arrange them together in order to produce a product/part family, which increases the barriers to implement customisation. The one-of-a-kind nature of products manufactured by this type of companies, lead them to use process layouts where equipment's are arranged according to their functions. Moreover, in ETO companies, a large amount of manual assembly operations is usually present. This imply a larger difficulty in implementing modularity. In addition to that, A/ETO presents low levels of diagnosability implemented. However, this characteristic is very important for them, because they need to reconfigure the manufacturing system frequently to accommodate variations in the product mix. The lack of diagnosability may dictate slow ramp up and low-quality level. Diagnosability can be embedded if the system includes in-process inspection resources that allow the detection of quality defects in real time. In practice, this is implemented by installing reconfigurable inspection machines at a separate stage in the system, which allows the inspection to be conducted in a contaminant-free environment and can be bypassed if necessary (Koren, 2013). Therefore, A/ETO production systems presented lower levels of implementation of modularity, customisation and diagnosability than MTO due to the difficult of implementation of these characteristics, not because they are less necessary. In this companies, customisation might be very hard to improve due to the high mix of one-of-a-kind products. Nevertheless, an effort should be made to improve modularity and diagnosability, leading to more reconfigurable and, consequently, flexible, production systems. This seems to indicate that further research is required to understand how to implement these two core characteristics of reconfigurability in A/ETO production systems. Increasing modularity might be achieved by considering the use of collaborative robots for assembly lines or modular CNC machines (Koren et al., 1999). On the other hand, the use of portable inspection equipment could lead to an increase in diagnosability for these companies.

In MTS, although the products are manufactured based on demand forecasts, customisation was the characteristic ranked in the first place. While in MTO and A/ETO production systems customisation implies that the manufacturing equipment and system are designed to process a single product/part, in MTS, this characteristic indicates the design of the manufacturing equipment and system around a product/part family, with enough flexibility to manufacture this family. The diagnosability, that was ranked second, represents the design for easy diagnosis. In other words, it allows the identification and the diagnostic of products defects, and the correction of operational deficiencies quickly (Benderbal et al., 2018b). Adaptability was ranked third, but presented lower values than the other types of production systems. This characteristic is important to MTS, because they may be subjected to variations in demand volume, which requires adjustments in the throughput capacity. The implementation of adaptability can help in the process of physical changes of production capacity and throughput improvement, in a more efficiently way. MTS production systems require more static and physical changes of production capacity, while MTO and A/ETO tend to require dynamic and logical scalability with a very short time horizon, *e.g.* in terms of batch sizes of one or highly customised products (Andersen et al., 2018a). For this reason, MTS manufacturing companies invest more in the implementation of adaptability, than integrability and modularity, that were the least ranked characteristics. Indeed, these last two characteristics are less important, because MTS companies have a stable mix of products. Furthermore, MTS environments need technologies that enhance and facilitate the improvement of adaptability in order to be more flexible. For example, the process industry, normally focused on process productivity, is facing the need to be market driven (Napoleone et al., 2018).

4.6 Conclusions

In this chapter, a comparison of the aggregated measure of reconfigurability was made, considering companies that adopts different business production strategies: MTO, A/ETO and MTS. This aggregated measure can be useful to understand the need of reconfigurability in manufacturing companies with different production systems and in the process of deciding which of the core characteristics requires more attention in order to increase the reconfigurability implemented. Five core characteristics were considered, namely modularity, integrability, customisation, adaptability and diagnosability. This study used a questionnaire-based methodology. The reliability and validity analysis indicate that this measurement instrument is reliable and valid.

The findings suggest that the core characteristics can contribute to manufacturing companies that adopt MTO, A/ETO and MTS production systems in different ways. However, each of them has specific requirements, such as variability in demand volume and product mix, that influence the need of reconfigurability for the manufacturing system.

This study has considered equal weights for each core characteristic to calculate the aggregated measure of reconfigurability. Future research could investigate how the core characteristics interact, for instance, whether they possess similar or different behaviour, and whether one impacts positively or negatively on another. This may contribute to understand the extent to which each characteristic contributes to achieving reconfigurability, thus providing more realistic insights for weighting each of them. Moreover, multicriteria decision techniques, such as analytical hierarchical process (AHP) and fuzzy AHP, can be combined to the questionnaire-based methodology to attribute weights and calculate a reconfigurability index.

Part III Systematic literature network analysis

Contents

Chapter 5 The layout design in Reconfigurable Manufacturing Systems: a literature review

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Abstract

The layout is an important issue in the design of manufacturing systems. In conventional systems, the layout rarely changes after the initial design. However, as the market demands are changing more rapidly and frequently, layout configurations must be capable of quickly reconfiguring the arrangement of resources to suit new production mixes and volumes, while minimising material handling and relocation costs and maximising savings in material flow and inventory costs. This chapter presents a literature review on the layout design of RMS, which have been attracting more and more attention in recent years. A systematic literature network analysis (SLNA) was applied to identify trends, evolutionary trajectories and key issues that are influencing the development of knowledge in this field of study. The results are analysed and discussed using a bibliometric and a chronological citation network analysis (CNA). A trend towards the investigation of four perspectives: RMS design methodologies, RMS core characteristics for configuration selection, layout design and solution approaches, suggests that the layout design of RMS cannot be seen in isolation. The results also demonstrate that solution approaches based on meta-heuristic techniques are widely used in layout design. Finally, this chapter identifies gaps in the literature and suggests directions for future research on the layout design of RMS.

5.1 Introduction

RMS were proposed by Koren et al. (1999) to cope with varying product demand and the fast introduction of new products, which are the consequence of unpredictable market changes and a ferocious global competition (Benderbal et al., 2017b). RMS can provide a significant reduction of costs and time in the launching of new products and in the integration of a new manufacturing process into existing systems (Renzi et al., 2014). Thus, it is expected that RMS should be capable of responding to the rapid changes in technology and fluctuations in market demand, while guaranteeing shorter lead times, lower inventory levels, material flow efficiency and minimum relocation costs (Hasan et al., 2014). In fact, they seem to be appropriate to cope with abrupt production changes, since they can be adjusted with minimal effort and low costs, in a manufacturing environment where a high level of uncertainty exists (Wang, 2011b).

Since the late 1990s, the challenges of designing RMS have been highlighted (Koren et al., 1999; Xiaobo et al., 2000b; Youssef and ElMaraghy, 2008; Saxena and Jain, 2012; Dahane and Benyoucef, 2016). The design process for RMS can be broken down into three phases: layout design, material handling system design/selection and control system specification (Oke et al., 2011). This chapter focuses on the layout design. In conventional manufacturing systems, this problem deals with assigning m machines to n locations, in such a way that the sum of the fixed investment (or installation costs) and the sum of associated material handling costs are minimised (Oke et al., 2011). However, the layout design in RMS needs to take into consideration not only the current product to be produced and classical constraints (*e.g.* precedence relations and machine capabilities), but also new specificities of RMS, such as the whole product family and the transition that may occur when switching from one product to another in this product family (Benderbal et al., 2017b). Therefore, under these conditions, the effectiveness of a given layout should be measured by its ability to adapt to this changing production scenario (Singh and Sharma, 2006; Abbasi and Houshmand, 2011; Kheirkhah et al., 2015).

Facility layouts are known to greatly impact on manufacturing systems' performances (Drira et al., 2007). A primary advantage of reconfiguring a layout is that the cost of handling materials can be minimised because equipment can be reconfigured to suit the new production mix and volume. Due to the short life of a given layout and the availability of production data for a given period, it is possible to consider optimising operational performance measures such as minimising part cycle times and work in progress (WIP) inventories (Meng et al., 2004). The frequent reconfiguration and redesign of the layout must maintain the system's high performance (*e.g.* productivity, responsiveness and maintainability) that can be achieved by integrating performance metrics at the outset of the layout design process (Benderbal et al., 2017b).

The potential of frequently reconfiguring layouts, in a sense, transforms the layout design from a strategic problem, in which only long-term material handling costs are considered, to a tactical problem, in which operational performance measures are considered in addition to the costs of handling materials and machine relocation when changing from one layout configuration to the next (Meng et al., 2004).

Layout design has been studied for several decades and many literature reviews have already been published (Drira et al., 2007; Singh and Sharma, 2006; Anjos and Vieira, 2017; Hosseini-Nasab et al., 2018). Investigations on this topic in specific typologies of manufacturing systems have also been performed, *e.g.* focusing on cellular manufacturing systems (CMS) (Askin, 2013; Houshyar et al., 2014) and FMS (Moslemipour et al., 2012). In recent years, managing the positioning of resources within an RMS layout has been attracting the interest of a large number of researchers and practitioners that need to respond to the increasingly frequent introduction of new products, changes in existing products, large fluctuations in product demand and mix, changes in governmental regulations and changes in process technology (Benderbal et al., 2017b; Dahane and Benyoucef, 2016). Nevertheless, research efforts have been mainly focused on RMS modelling and the generation of process plans (Benderbal et al., 2017b). There are very few works on the layout design of RMS, where there is a significant gap. This work analyses the existing literature on the layout design of RMS, highlighting the main contributions, evolutionary trajectories and research focuses over the past years. The aim of this chapter is to add a review of the literature in this field of knowledge, which may make a contribution by suggesting lines for future research and facilitating theory building.

The remainder of this chapter is organised as follows. The methods are described in section 5.2. The application of the methods and the results obtained are provided in section 5.3. The findings are discussed in section 5.4. Suggestions for future research are presented in section 5.5. Finally, section 5.6 draws conclusions and establishes the limitations of this research.

5.2 Methods

The SLNA, as described in Colicchia and Strozzi (2012), was adopted to conduct the literature review on the layout design of RMS. This procedure consists of two phases. The first phase is systematic literature review (SLR), which is defined by means of three steps: (1) the definition of the scope of the analysis; (2) locating studies, using suitable keywords; and (3) the selection and evaluation of the studies retrieved. The output of the first phase is a set of selected papers.

This set of papers is analysed and discussed in the second phase, using a bibliometric and a chronological CNA to verify the dynamic behaviour of the topic researched over time. A main path analysis was developed to provide a dynamic perspective of the existing literature, as well as to identify trends, evolutionary trajectories and key issues that are presently influencing the development of the layout design of RMS. Nevertheless, only considering citations to delineate a research field is not enough. To overcome this limitation, the CNA was combined with a co-occurrence analysis of keywords, which can be helpful to detect research patterns and trends embracing the information available in all papers (Ding et al., 2001).

Two different software packages were adopted to build the networks. Sci2Tool was used to analyse the datasets and to generate the input file for the citation analysis, which was conducted through Pajek, one of the best known and most frequently used software to analyse network data.

5.3 Results

5.3.1 Systematic literature review

Scope of the analysis

Designing is among the most active research topics in the field of RMS (Benderbal et al., 2017a,b). The design process for RMS (Figure 5.1) can be broken down into three phases: layout design, material handling system design/selection and control system specification (Oke et al., 2011). Layout design includes the choice of machines and the layout of the manufacturing system. The choice of machines is related to the selection of machines to be included in the layout. The layout of the manufacturing system concerns the layout problem, which is the assignment of the machines selected to their locations. The task of the design/selection of the material handling system consists in determining the material handling system to be used, calculating the unit loads or batch size for the system, assigning specific equipment to departmental moves and developing the flow path for the system. Control system specification involves the interrelationship between workstations, machines in the workstations, components, tooling and personnel, besides the coordination at the auxiliary buffer of the direction of the material handling system and the acceptance and delivery of WIP from one material handling system to another.

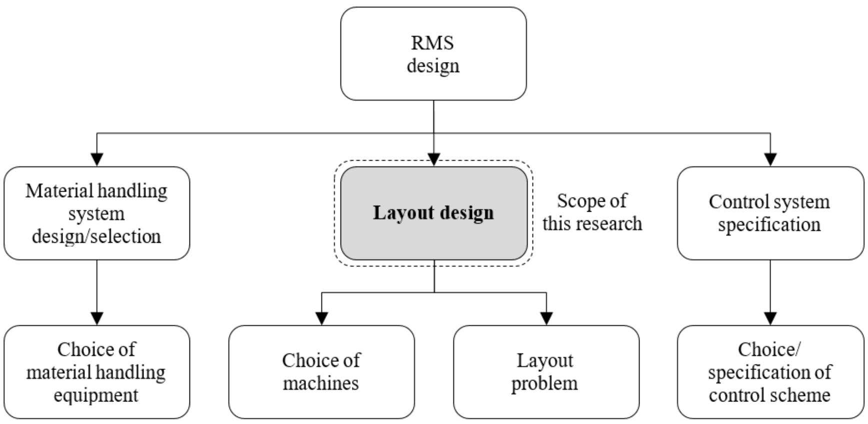


Figure 5.1: The design process for RMS (Oke et al., 2011).

This chapter focuses on the layout design, which has gained attention due to the degree of uncertainty and unpredictability (*e.g.* fluctuations in market demand and volume) that characterise manufacturing companies, which need a high level of responsiveness to changes (Benderbal et al., 2018a).

Locating studies

Locating studies is a critical process, because results may change if different keywords are used. A set of keywords was identified, with the aim of linking the subject and the objectives of this study. They were specifically designed in order to select relevant papers and avoid too generic and dispersed results. Since this process could imply a certain degree of subjectivity, a panel of academic experts was consulted to validate the search. The keywords chosen were: ‘reconfigurable layout problem’, ‘layout reconfigurability’, ‘reconfigurable manufacturing system design’, ‘reconfigurable facility layout’, ‘reconfigurable layout design’, ‘RMS configuration’ and ‘RMS design’. The keywords did not include synonyms of ‘reconfigurable’ or related words (*e.g.* adaptable, flexible and changeable), because it might defocus the search. Additionally, specific terms related to the main characteristics of RMS were not included in the set of keywords, because they would overly restrict the number of papers retrieved. These choices were discussed and validated by the experts and were used in compliance with the objective of this chapter that focuses on the layout design of RMS. The process of locating studies is summarised in Figure 5.2.

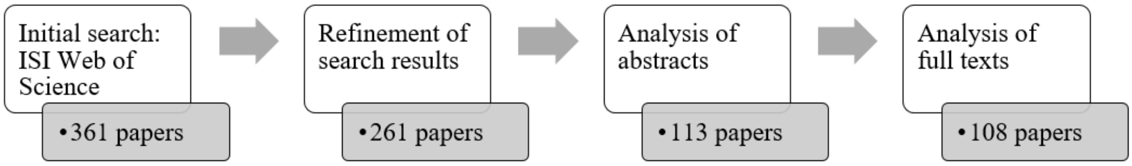


Figure 5.2: Summary of the process of locating studies.

Study selection and evaluation

The data used were collected from the Web of Science that has been the most commonly used academic database for citation analysis studies to date, because the data recovered are ‘cleaner’ than the ones from other databases, yielding a unique identification of papers and, consequently, a more reliable analysis of the citation network. The search was conducted in late August 2018. 108 papers, from 1998 to 2018, were selected from the total of papers retrieved, allowing the identification of the most relevant papers and an initial selection of the main contributions to the research of the layout design of RMS. Only papers published in English, articles in peer-reviewed journals and international conference proceedings were considered. 76 papers were retrieved from journals and 32 from international conference proceedings. The top five journals that published the highest number of papers contained in the sample are presented in Table 5.1.

5.3.2 Citation network analysis

The 108 papers were included in the chronological CNA in order to investigate the process of knowledge creation, transfer and development, regarding the layout design of RMS. The CNA is the most common technique used to assess the scientific importance of papers, authors and journals, and for extracting specialties and research traditions from citations. By

Table 5.1: Top five journals on layout design of RMS and the number of papers sampled.

Journal	Number of papers
International Journal of Production Research	19
International Journal of Advanced Manufacturing Technology	10
Journal of Manufacturing Systems	6
Computers & Industrial Engineering	5
International Journal of Computer Integrated Manufacturing	3

analysing the citation network, it is possible to identify the dynamic behaviour of the subject under study over time (Nooy et al., 2011). The successful adoption of this approach in other similar contexts proves that it is a good choice for the topic under investigation, due to its potential to identify trends and key issues that influence the development of knowledge within a particular field of study. Besides, it is a more scientific approach compared to traditional descriptive reviews. Traditional reviews fail to encompass the evolutionary aspect of a field of study and rely on subjective criteria to select papers and classify research contributions in pre-defined coding schemes, while the CNA relies on objective measures and algorithms to perform quantitative literature evaluation based on the detection of emerging topics (Colicchia and Strozzi, 2012).

The citation network related to this study is composed of isolated nodes and connected components. Researchers operating within a particular field of study tend to cite each other and common precursors, revealing cohesive subgroups. Weak components identify isolated scientific communities that are not aware of each other or who see no substantial overlap between their research domains (Nooy et al., 2011). Since the CNA is a method based on citations, the isolated nodes were excluded from the analysis.

Main path

If knowledge flows through citations, a citation that is needed in paths between many papers is more crucial than a citation that is hardly needed for linking papers. Among all possible paths, from the most recent to the oldest, the network algorithm computes the paths that are most frequently found. This method does not involve the absolute count of the maximum number of citations received, but the simultaneous computations of all possible paths through the sample dataset and the choice most frequently found through time (Nooy et al., 2011).

The most important citations constitute one or more main paths, which can be considered the backbones of a research tradition. Main path analysis calculates the extent to which a particular citation or paper is needed to link papers, which is called the traversal weight of a citation paper. In order to extract the main path from the citation network, the traversal weights were quantified using the search path count (SPC) method. It counted the paths between all sources (*i.e.* a paper that is not citing any others) and sinks (*i.e.* a paper that is not cited by others) (Nooy et al., 2011). The extraction of the main path was conducted with Pajek software, using the key-route algorithm. This algorithm searches for all the main paths containing selected key-routes with the highest overall sum of weights. The key-route search guarantees that significant top links in the citation networks are included in the main paths (Nooy et al., 2011). The key-route main path is the most relevant path among the main paths and is a particularly good tool to visualise the development structure of a scientific research field (Liu and Ly, 2012). The key-route, extracted from the CNA referred to in the previous section, is represented in Figure 5.3. This path identifies the main stream of the literature on the layout design of RMS, between 1998 and 2018.

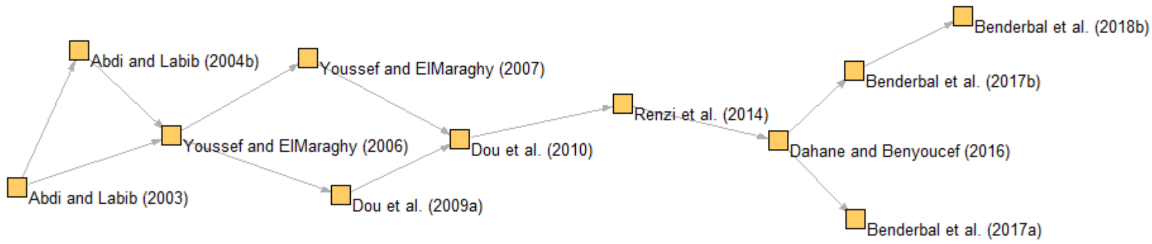


Figure 5.3: The key-route component of layout design of RMS.

Abdi and Labib (2003) is the source paper of the main path. They developed a design strategy for RMS, using the AHP, in order to select a typology of manufacturing systems from among feasible alternatives. The AHP model was used to structure a company's decision-making process, involving the specific manufacturing choices from among the existing manufacturing systems, RMS and a hybrid manufacturing system (*i.e.* a combination of both), concerning its strategic plan. The strategic objectives considered for designing RMS are responsiveness, cost, quality, inventory and the operator's skills. The authors also defined a reconfiguration link between market and manufacturing, in order to group products into families and select the appropriate family at each configuration stage. Later, Abdi and Labib (2004b) extended this work to the tactical level, to group products into families based on operational similarities, when machines are still not identified.

Youssef and ElMaraghy (2006) divided manufacturing system reconfiguration activities into two types: hard and soft. Hard (physical) reconfiguration activities include adding/removing machines and machine modules and changing material handling systems. Soft (logical) reconfiguration activities include re-programming machines, re-planning, re-scheduling, re-routing, and increasing/decreasing shifts or the number of workers. They developed a model to optimise the capital cost of RMS configurations with multiple aspects using genetic algorithms (GA), which can support system configuration selection decisions at the initial design and reconfiguration stage. The model considered the arrangement of machines (number of stages and number of parallel machines per stage), equipment selection (machine type and corresponding machine configuration for each stage) and the assignment of operations (operation clusters assigned to each stage corresponding to each part type) of a flow line. Youssef and ElMaraghy (2007) extended the model developed to consider the optimisation of the reconfiguration effort in addition to capital costs. Also, the solution approach was divided into two phases. In the first phase, tabu search (TS) was associated to GA to select the near-optimal alternative configurations for each possible demand scenario over the configuration periods considered, for the continuous optimisation of capital cost and system availability. The second phase utilised GA and TS to determine the alternatives, from those produced in the first phase, which would optimise the reconfiguration effort over the planning horizon.

Dou et al. (2009a) investigated a similar problem, but while Youssef and ElMaraghy (2006) considered a flow line with two different parts to be manufactured, they considered a single product flow line. These authors proposed a graph model to optimise capital cost in order to accommodate a new production line. They considered the number of workstations, number and type of machines, and assigned operations for each workstation as parameters of the single product flow line. Next, Dou et al. (2010) presented a GA-based approach to identify the best configuration among the k-best ones that optimised multi-part flow line configurations of RMS for a part family, comprising the number of workstations, the number of paralleling machines, machine types and assigned operation setups. This methodology proved to be more efficient in identifying the k-best configurations than the one proposed previously (Youssef and ElMaraghy, 2006).

Renzi et al. (2014) presented a state-of-the-art review on the design of RMS compared with DMS by means of optimisation, focusing on non-exact meta-heuristic and artificial intelligence methods. They identified four sub-problems regarding the design of manufacturing systems: cell formation, layout, scheduling and resource allocation problems. Cell formation problems concern grouping parts into families. In layout design, machines are positioned in each cell (intra-cell layout) or cells are configured with respect to another one (inter-cell layout). In scheduling problems, production operation processes are planned for single parts or part families. In resource allocation problems, tools and both human and material resources are assigned.

The layout design within the designing process of RMS (Figure 5.1) considers two main and distinct problems: the choice of machines and the layout problem (Oke et al., 2011). The first is related with the choice of machines to be included in the layout, while the second concerns the allocation of these machines in the layout process (Benderbal et al., 2017b). Dahane and Benyoucef (2016) focused on the first problem, using an adapted non-dominated sorting genetic algorithm-II (NSGA-II) to minimise the total cost, including the cost of using the machines and their maintenance, and to maximise the reconfiguration index, which is based on the global capacity of system reconfiguration and the reconfigurability required to manufacture the product. Benderbal et al. (2017a, 2018b) also addressed the problem of the choice of machines. In the first work, the authors developed a flexibility-based multi-objective approach using an adapted NSGA-II to select suitable machines from a set of potential ones, to ensure the best responsiveness of the system designed in case of a lack of availability of one of the machines selected. In the second, they developed a modularity-based multi-objective approach using an adapted archived multi-objective simulated annealing (AMOSA) and technique for order preference by similarity of ideal solution (TOPSIS) to solve an optimisation problem by selecting the most suitable machines from a set of candidates. The authors considered three objectives: maximisation of modularity, minimisation of completion time and minimisation of costs.

On the other hand, Benderbal et al. (2017b) addressed the layout problem in RMS. They described a multi-objective approach to assess the evolution and effort involved in the layout transition between products of a product family in RMS design. The layout evolution effort is minimised, and system performance metrics are maximised. The problem considered compatibility and productivity requirements as constraints and average machine utilisation and alternative replacement machines within the system as metrics, to ensure the high performance of the RMS designed according to the layouts generated.

The papers identified in the main path can be divided into two groups, plus an isolated work that addresses a literature review on the design of cellular RMS (Renzi et al., 2014). The first group includes Abdi and Labib (2003, 2004b), whose main contributions are to the strategic and the tactical level of RMS design. At the strategic level, Abdi and Labib (2003) described the distinctive features of systems, among which is the reconfiguration link, that groups products into families, and highlighted current and future requirements to achieve a reconfigurable strategy during its implementation period. At the tactical level, Abdi and Labib (2004b) applied this design strategy, in which the products were grouped into families, to select the product family aimed at in RMS design. They also emphasised the need to design modular products, in which different modules may contribute to various different products, thus sharing common resources. The second group includes Youssef and ElMaraghy (2006, 2007); Dou et al. (2009a, 2010), who provided solutions for the arrangement and the choice of machines, and the assignment of tasks and operations of single part flow lines or multi part flow lines, and Dahane and Benyoucef (2016) and Benderbal et al. (2017a,b, 2018b), who contributed to the choice of machines and layout problems in RMS.

Although this research focused on the layout design of RMS, the first group of the main path does not address this problem directly, but its importance within the RMS design process (Abdi and Labib, 2003, 2004b). Research focusing specifically on the layout design, including the choice of machines and the layout problem, emerged only later. The earliest studies (Youssef and ElMaraghy, 2006, 2007; Dou et al., 2009a, 2010) addressed the layout design of RMS in assembly lines, which are relatively simple when compared to other manufacturing systems' typologies. However, recently, the layout design of RMS has been investigated in more complex manufacturing systems (Dahane and Benyoucef, 2016; Benderbal et al., 2017a,b, 2018b), leading to a greater specialisation of the problem, because, in these cases, the choice of machines and the layout are addressed separately, in order to be able to cope with problems that assume a high level of complexity.

5.3.3 Co-occurrence analysis of authors' keywords

An analysis of authors' keywords can be helpful to detect research trends covering the information available in the content of papers. In this research, the network of the author's keywords of all the papers selected was studied. A co-occurrence network was built to analyse these keywords. In this co-occurrence network, nodes are the author's keywords from the 108 papers and the link weights represent how many times the words appear together in the same paper. Co-occurrence analysis assumes that the authors' keywords describe a paper's contents or the links that papers establish between themes appropriately. The presence of many co-occurrences around the same word or pair of words may correspond to a research theme and it reveals patterns and trends in a specific discipline (Ding et al., 2001).

To perform the co-occurrence analysis, the keywords from the 108 papers identified in the SLR were extracted. These keywords were normalised, *i.e.* separated into token words, normalised in lowercase, dots from acronyms removed, and the 's' at the end of words and stop words were deleted. As a result, the co-occurrence network was built, considering keywords that appeared together at least five times. The keyword network was analysed using the visualisation of similarities (VOS) clustering. The VOS clustering technique is closely related to the well-known techniques of multidimensional scaling, which has a long history in the statistical literature (Waltman et al., 2010). This technique is used to find communities in the network. It has a resolution parameter, in which the VOS quality function is optimised. Line values are always taken as positive, thus this algorithm is not suitable for signed networks (Nooy et al., 2011). The results obtained from analysing the co-occurrence of the authors' keywords point to the existence of four clusters, which are shown in Figure 5.4. The keyword clusters were analysed to identify research trajectories together with the description of some works and subjects.

Cluster 1: RMS design methodologies

Although the SLR and data collection were aimed at studies on the layout design of RMS, this first cluster contains 22 papers that present methodologies for the design process of RMS. This is expected, since the layout design is a phase within the RMS design process (Oke et al., 2011). Indeed, the papers in this cluster emphasise the importance of the layout design of RMS, since all the methodologies developed, despite using different terminologies, describe design phases that include the choice of machines and the layout problem. Moreover, they recognise that designing the layout is an important issue, because different configurations have a significant impact on profits (Xiaobo et al., 2000a).

For instance, Xiaobo et al. (2000a) proposed a framework for a stochastic model of an RMS, considering three issues: the optimal configurations in the design, the optimal se-

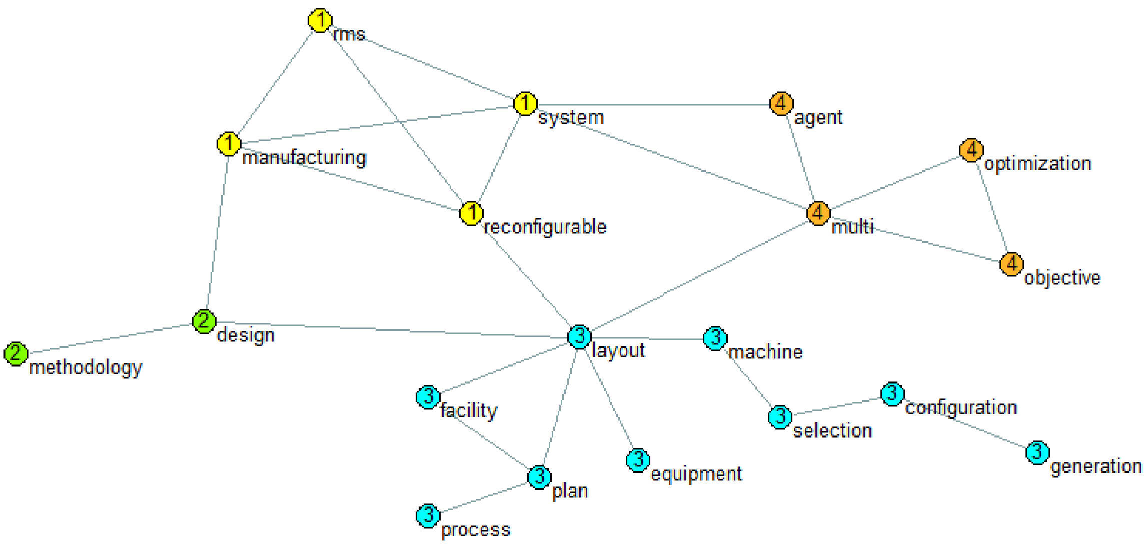


Figure 5.4: Co-occurrence network of the authors' keywords.

lection policy in the utilisation and the performance measure in the improvement. Saxena and Jain (2012) presented an RMS configuration design methodology composed by three phases, in which phase 1 is aimed at the identification and modelling of RMS evolution requirements for change in production volume and mix over time to provide the desired functionality and capacity; phase 2 uses a pre-processing procedure to reduce the model size and develops RMS configuration alternatives; and phase 3 is aimed at the selection of optimal configuration alternatives. Deif and ElMaraghy (2006) presented an open mixed architecture that describes different design processes starting from capturing the market demand to generating and selecting the best configuration that satisfies this demand to the final physical implementation of that system configuration for the design of RMS. Benkamoun et al. (2013) distinguish approaches about the design of reconfigurable assembly systems (RAS) from those which facilitate the reconfiguration of systems using integrated design (product selection, product design or process design). They also highlight the definitions of physical layout (arrangement of workstations) and logical layout (task assignment, with or without resource selections). Andersen et al. (2017) synthesised current contributions to RMS design in a generic method, composed by five phases: (1) management and strategic planning, which covers planning and strategic decisions, including the justification of investments and potential in RMS; (2) clarification of design task, which includes the definition of systems' requirements and the need for reconfigurability; (3) basic design, which identifies product families and decides which type, level and degree of reconfigurability will be emphasised as changing elements; (4) advanced design, which concerns the detailed design of modules, in terms of logical and physical aspects; and (5) reconfiguration, which consists in selecting configurations during operating time and deciding when and how to reconfigure the manufacturing system during its lifetime.

Some current challenges of designing RMS were also highlighted in this cluster.

Designing RMS is a demanding task for engineers due to the inherent complexity of the problem from a technical and economical point of view. Many technical requirements have to be considered simultaneously to realise an actual reconfigurability (Renzi et al., 2014). Indeed, the design of RMS represents a significant challenge compared to the design of conventional manufacturing systems, as it should be designed for the efficient production of multiple variants, as well as multiple product generations over its lifetime (Andersen et al., 2017).

Cluster 2: RMS core characteristics for configuration selection

The 25 papers within this cluster address the configuration selection for RMS, focusing on its core characteristics.

Koren and Shpitalni (2010) have described the design principles for RMS and a set of six core characteristics that provides reconfigurability for manufacturing systems and, consequently, for layout reconfigurations. Modularity is the compartmentalisation of operational functions into units that can be manipulated between alternate schemes for an optimal arrangement. Integrability is the ability to integrate modules, rapidly and precisely, by hardware and software interfaces. Customisation is the system or machine flexibility limited to a single product family. Convertibility is the design for functionality changes. Scalability is the design for capacity changes. Diagnosability is the capability of automatically reading the current state of a system to detect and diagnose the root causes of output products' defects and correct operational problems, in other words, it is the design for easy diagnostics. A system that has these core characteristics presents a high level of reconfigurability (Koren and Shpitalni, 2010).

The majority of papers in this cluster address the aforementioned six characteristics (Abbasi and Houshmand, 2011; Rabbani et al., 2014; Lee and Tilbury, 2007; Padayachee and Bright, 2014; Niroomand et al., 2014; Koren et al., 2016; Bruccoleri et al., 2005). Nevertheless, other different characteristics have been put forward to a lesser extent, such as agility (Hasan et al., 2012b), sustainability (Aljuneidi and Bulgak, 2016), commonality, compatibility and reusability (Galan et al., 2007). These studies argue that the effectiveness of RMS depends on implementing the core characteristics in the design as well as utilisation stage (Abbasi and Houshmand, 2011). Moreover, the manufacturing system layout must be designed at the outset for future expansions in its throughput to enable growth in supply exactly when needed by the market. The layout design for scalability allows the company to build a manufacturing system to supply the current demand and upgrade its throughput in the future, in a cost-effective way, to meet possible higher market demand in a timely manner (Koren et al., 2016).

In designing configurations for manufacturing systems, the layout of stations and the assignment of tasks to these stations are critical design issues. A system's configuration can facilitate or impede its productivity, responsiveness, convertibility and scalability, and can also impact on its daily operations. Multi-stage manufacturing systems can allow for several operational configurations, depending on how the machines are arranged in the stages and how they are connected via the material handling system (Koren and Shpitalni, 2010). Therefore, considering the core characteristics in the layout design is essential, because the ultimate goal of RMS is achieving reconfigurability.

Moreover, the core characteristics were also considered in the evaluation of RMS configuration (Singh et al., 2007; Li et al., 2007). However, the major concern when selecting the optimal configuration for RMS is the cost (Youssef and ElMaraghy, 2006; Dou et al., 2010; Niroomand et al., 2014; Spicer and Carlo, 2007). The objective of RMS layout is to achieve optimal economic cost within the overall life cycle. The system's configuration and technologies of economic cost evaluation are very important system-level enabling technologies of RMS (Li et al., 2007). The configuration of RMS and the way that RMS evolve from one configuration to another might affect the manufacturers' future investment costs. This is mainly due to the differences in the layout structure and convertibility characteristics of a configuration (Niroomand et al., 2014). Furthermore, RMS configurations should not only be capable of satisfying the demand requirements of each corresponding period, but should also be economical in terms of the capital cost of investment (Youssef and ElMaraghy, 2006).

Cluster 3: layout design

This cluster contains 37 papers that address the layout design of RMS, which includes the choice of machines and the layout problem (Oke et al., 2011). There are 16 papers that deal with the first issue. Most of them concern the choice of machines for an RMS given an available set, assuming that this problem occurs when a new production system is being built and the designer has already established a list of candidate machines (Benderbal et al., 2017a). They considered minimising capital costs, space and investment limitations, capacity and precedence constraints among operations, and performance measures such as, cycle times, storage levels and investments, to select the best machines (Benderbal et al., 2017a; Dou et al., 2009b).

Others include the task assignment to the machines, considering machine availability, the development of an index of systems' robustness for machine selection and the modification of the machines' capabilities (Youssef and ElMaraghy, 2008; Bensmaine et al., 2013; Benderbal et al., 2015). In the layout design of RMS, the assignment of tasks to stations and the layout arrangement are important issues (Bensmaine et al., 2013). The process plan describes the schedule of operations, that is, which operation is assigned to which machine in each configuration (machine configuration) and in what order. The assignment of operations to machines is done during the generation of the process plan, thus, machines that will be selected are those involved in the production, *i.e.* from those appearing in the process plan (Benderbal et al., 2018b).

Furthermore, the modification of the machines' characteristics leads to the concept of RMT that are capable of performing a variety of operations in their existing configurations and their functionality can further be changed by just changing their modules. RMT lies at the heart of RMS, imparting distinguishing features such as customised functionalities and adjustable capacity through its changeable structure (Goyal et al., 2013). Several papers within this cluster consider the utilisation of RMT to provide flexibility and customisation for manufacturing systems, since the displacement of machines can be difficult or unfeasible (Benderbal et al., 2018b; Goyal et al., 2013; Molina et al., 2005; Goyal et al., 2012; Eguia et al., 2017).

On the other hand, there are 21 papers that deal with the layout problem of RMS. Among them, two conceptual papers highlight the need to design more flexible, modular and reconfigurable layouts for dynamic and uncertain environments (Benjaafar, 2002; Maganha and Silva, 2017). Furthermore, 12 works address practical applications of the layout problem in RMS. Taking into account the complexity of this type of problem, these studies assumed it as an optimisation problem and proposed various solutions, such as a stochastic model to select the optimal configuration for product families (Xiaobo et al., 2000b), an equipment layout assignment algorithm (ELAA) to find the near optimal equipment layout in order to reduce the cycle time of core products (Kuo, 2001), particle swarm optimisation (PSO) to optimise the layout of the manufacturing cell and the allocation of transport robots (Yamada et al., 2003), an open queuing network-based analytical model to solve the reconfigurable layout problem (Meng et al., 2004), a revised electromagnetism-like mechanism (REM) for the layout design using an automated guided vehicle (Guan et al., 2012) and mixed integer programming (MIP) to solve a multi-facility layout problem (Azevedo et al., 2013, 2017; Purnomo and Wiwoho, 2016). A general simulation framework was also proposed, in order to provide the outputs of the layouts and costs, as well as to analyse the benefits and performance of RMS, based on the variation of products, quantity and order lead time (Cedeno-Campos et al., 2013; Zheng et al., 2013).

Moreover, 7 papers deal with the re-layout of existing production systems (Bejlegaard et al., 2015; Ren et al., 2015; Vitayasak and Pongcharoen, 2015). The re-layout involves rearranging existing equipment in a facility (Lacksonen and Chao-Yen, 1998). Lacksonen and Chao-Yen (1998) proposed a two-criteria MIP model to find the schedule that minimises department move costs subject to precedence constraints. Ferrari et al. (2003) developed an integrated approach on the automatic design of a plant layout, considering qualitative and quantitative criteria. Wang (2011a) and Keshavarzmanesh et al. (2010) investigated the re-layout of a shop-floor, dividing the layout problem into two sub-problems: the re-layout and find-route. Based on the source of uncertainty, GA is used where changes cause the entire re-layout of the shop, while function blocks are utilised to find the best sequence of robots for the new conditions within the existing layout.

In conventional manufacturing systems, the layout is rarely changed after the initial system design. However, as market demands are changing rapidly, manufacturers are required to provide numerous products in a limited time in a cost-effective manner. This is why the layout of RMS should be redesigned and reconfigured frequently (Guan et al., 2012). Thus, the layout design of RMS, including the choice of machines and the layout problem, is a key issue in order to respond to such requirements.

Cluster 4: solution approaches

This cluster contains 24 papers that describe the most used methods to solve design and layout problems. The RMS design belongs to the NP-hard family of combinatorial problems (Renzi et al., 2014; Wang, 2011a). Most researchers consider them as optimisation problems, with single or multi objectives, each with its own unique characteristics. The objectives may include minimising the total distance of transport paths, total cost and completion time, capital costs of configurations, handling costs of materials, overall production time, investment in equipment and effective utilisation of space; providing for employee safety and comfort; flexibility for rearrangement and operations; and facilitating the manufacturing process. Many works in the literature rely on PSO (Yamada, 2006; Yamada and Lei, 2006), GA (Dahane and Benyoucef, 2016; Dou et al., 2008; Kant et al., 2017; Qiu et al., 2005) and ant colony optimisation (ACO) (Maniraj et al., 2017) for the optimisation of the layout design for manufacturing systems.

Other approaches were considered, but to a lesser extent. In a manufacturing system where the static layout of a multi machine factory is integrated with a set of mobile robots, Giordani et al. (2009) used a multi agent system (MAS) model to determine the position of the robots in each period of the planning time horizon. The MAS paradigm offers an alternative way to design manufacturing systems based on a decentralised control using distributed, autonomous agents, thus replacing the traditional centralised control approach. MAS solutions provide modularity, flexibility and robustness, thus addressing the responsiveness property, but do not usually consider true adaptation and re-configuration (Leitao et al., 2012). Leitao et al. (2012) analysed some of the existing bio-inspired applications (*e.g.* ACO, GA and PSO) and the real benefits of bio-inspired MAS for solving manufacturing problems. Indeed, bio-inspired MAS may offer an alternative way of designing intelligent, robust and adaptive systems that replace traditional centralised control. Kulturel-Konak et al. (2007) proposed a bi-objective approach to solve a re-layout problem for cases of fixed and expanded facility areas, using TS to minimise material handling and re-layout costs. Wang et al. (2008) proposed a simulation optimisation methodology to resolve the facility layout problem. Simulation models are used to evaluate the performance of candidate facility layouts schemes and the results of evaluation are returned to the GA to be utilised in the selection of the next generation of candidate facility layout schemes to be evaluated, until a satisfactory solution is obtained.

In Table 5.2, the main contributions and the references of each cluster are summarised.

Table 5.2: Summary of each cluster's main contributions and references.

Cluster	Main contributions	References
RMS design methodologies	Development of RMS design methodologies, but with a large variety in terminologies, level of details and number of phases Differences between conventional manufacturing systems' design and RMS The importance of the layout design within the RMS design process	Abdi and Labib (2003), Abdi and Labib (2004b), Abdi and Labib (2004a), Al-Zaher et al. (2013), Deif and ElMaraghy (2006), Bensmaine et al. (2013), Andersen et al. (2017), Izquierdo et al. (2009), Jefferson et al. (2016), Kamrani (2003), Kochhar and Heragu (1999), Koren et al. (2018), Li et al. (2009), Moghaddam et al. (2018), Oke et al. (2011), Renzi et al. (2014), Saxena and Jain (2012), Unglert et al. (2016c), Unglert et al. (2016b), Unglert et al. (2016a), Xiaobo et al. (2000a), Zhang et al. (2014)
RMS core characteristics for configuration selection	The effectiveness of RMS layout depends on implementing RMS core characteristics Considering RMS core characteristics when selecting configurations for manufacturing systems can facilitate or impede their productivity and responsiveness, and impact on their daily operations Core characteristics can be used to evaluate RMS layout configurations	Abbasi and Houshmand (2011), Aljuneidi and Bulgak (2016), Benama et al. (2014), Bruccoleri et al. (2005), Dou et al. (2007), Farid (2013), Galan et al. (2007), Guerra-Zubiaga et al. (2005), Hasan et al. (2012b), Huang et al. (2010), Kahloul et al. (2016), Koren and Shpitalni (2010), Koren et al. (2016), Lamotte et al. (2006), Lee and Tilbury (2007), Li et al. (2007), Chao et al. (2007), Niroomand et al. (2014), Orozco and Lastra (2007), Padayachee and Bright (2014), Rabbani et al. (2014), Singh et al. (2007), Spicer and Carlo (2007), Tang and Qiu (2004), Wang et al. (2009)
Layout design	Practical investigations on the choice of machines given an available set, layout problems in RMS and re-layout of manufacturing systems Conceptual papers that highlight the need for more reconfigurable layouts Studies combining the choice of machines and the assignment of tasks, and layout and routing problems RMT to provide flexibility and customisation for manufacturing systems	Baqai and Shafiq (2013), Benderbal et al. (2015), Benderbal et al. (2017a), Benderbal et al. (2018b), Bensmaine et al. (2013), Dou et al. (2009b), Dou et al. (2009a), Dou et al. (2010), Eguia et al. (2017), Goyal et al. (2012), Goyal et al. (2013), Molina et al. (2005), Schmidt (2013), Youssef and ElMaraghy (2006), Youssef and ElMaraghy (2007), Youssef and ElMaraghy (2008), Azevedo et al. (2013), Azevedo et al. (2016), Azevedo et al. (2017), Benjaafar (2002), Cedeno-Campos et al. (2013), Guan et al. (2012), Benderbal et al. (2017b), Kuo (2001), Maganha and Silva (2017), Meng et al. (2004), Purnomo and Wiwoho (2016), Xiaobo et al. (2000b), Yamada et al. (2003), Zheng et al. (2013), Bejlegaard et al. (2015), Ferrari et al. (2003), Keshavarzmanesh et al. (2010), Lacksonen and Chao-Yen (1998), Ren et al. (2015), Vitayasak and Pongcharoen (2015), Wang (2011a)
Solution approaches	Meta-heuristic techniques to deal with the layout design of RMS and to solve the layout problem	AlGeddawy and ElMaraghy (2010a), AlGeddawy and ElMaraghy (2010b), Dahane and Benyoucef (2016), Dou et al. (2008), Fan et al. (2011), Giordani et al. (2009), Hsieh (2018), Jiang et al. (2014), Kant et al. (2017), Kheirkhah et al. (2015), Kia et al. (2012), Kia et al. (2013), Kulturel-Konak et al. (2007), Leitao et al. (2012), Lin and Murata (2010), Lv et al. (2010), Maniraj et al. (2017), Ming et al. (2007), Qiu et al. (2005), Shafigh et al. (2017), Wang et al. (2008), Wu and Ning (2006), Yamada (2006), Yamada and Lei (2006)

5.4 Discussion of the findings

An overview of the main path highlights the most active authors in the field of layout design of RMS. The first group of papers (Abdi and Labib, 2003, 2004a) contributes to RMS design methodologies, such as the papers identified in cluster 1. These investigations highlight the importance of the layout design within the RMS design process. The results show that all different methodologies that have been developed include the choice of machines and the layout problem as a phase of the design process, but use different terminologies. Despite the numerous contributions to this research area, there is not a consensus concerning the phases, nor of the positioning of the layout design in the RMS design process. There is little agreement on the structure of the RMS design process, which is largely due to varying terminology, level of detail and whether a phased or cyclic perspective of design is applied (Andersen et al., 2017).

Although there is a significant difference between the design of conventional manufacturing systems and RMS, which increases the complexity of the processes and the difficulty of effectively implementing reconfigurability, the majority of these design methodologies have been developed based on conventional manufacturing system design methods that do not support the RMS design (Benderbal et al., 2018b; Andersen et al., 2017). The design of conventional manufacturing systems has been upgraded due to the rapid development of new technologies. In an Industry 4.0 factory, the physical world of shop floor equipment merges with the virtual world of information and communication technology, leading to the concept of smart design (Zheng et al., 2018). Virtualised systems and physical machinery are implemented to support manufacturing activities and decision-making. Technologies and design software, such as virtual and augmented reality, computer-aided design and computer-aided manufacturing, can interact with physical systems in real time. These solutions are suitable to support customised configuration and decision making, as well as the development according to the uniqueness of many types of industries (Zheng et al., 2018). Therefore, engineering changes and physical realisations could be combined to achieve smart layout design.

The second group of the main path (Benderbal et al., 2017a,b; Dahane and Benyoucef, 2016; Benderbal et al., 2018b; Youssef and ElMaraghy, 2006, 2007; Dou et al., 2009a, 2010) provides solutions for the choice of machines and the layout problem, such as the papers identified in cluster 3. Both are important issues in the layout design of RMS (Koren and Shpitalni, 2010; Bensmaine et al., 2013). Cluster 3 presents a greater number of articles dealing with the layout problem in RMS, highlighting the increasing interest in this research topic. The majority of the studies assume the layout problem as an optimisation problem. Although most of them address the assignment of machines to their respective location, using different meta-heuristic techniques, none investigate what may trigger the need for a layout reconfiguration, which may be one of the most critical tasks in practice (Andersen et al., 2017).

In an Industry 4.0 factory, smart decision making requires real-time information sharing and collaboration (Zheng et al., 2018). Big data analytics plays an important role in processing real time data and abrupt changes in the product mix and volume, thus it may contribute to enabling the layout design at an affordable cost. With the support of smart design and smart decision-making, manufacturing industries can achieve a holistic perspective by considering practical concerns, such as production efficiency, logistics availability, time constraints and multiple criteria. Lightweight equipment, mobile and collaborative robotics may cope with the layout design, providing modular equipment, in which modules can be rapidly added/removed or easily displaced on the shop floor. Flexible transportation systems and reconfigurable controls, which are integrated in an open architecture environment, may also provide flexibility and reconfigurability to manufacturing systems' layouts (Zheng et al., 2018). The introduction of these new technologies implies the need to revise existing design methods for conventional manufacturing systems in order to consider new objectives and constraints to resolve the layout design in RMS.

Moreover, the findings indicate that the choice of machines in RMS is often investigated together with the assignment of tasks to machines (Youssef and ElMaraghy, 2008; Benderbal et al., 2018b; Dou et al., 2009a, 2010; Bensmaine et al., 2013; Benderbal et al., 2015). On the other hand, the layout problem is investigated separately from, or rarely related to, the routing problem (Keshavarzmanesh et al., 2010; Wang, 2011a). Only two works deal simultaneously with the choice of machines, the layout problem and the assignment of tasks (Youssef and ElMaraghy, 2006, 2007). Investigating the layout problem in isolation may lead to sub-optimal solutions. Therefore, more research integrating the choice of machines, the layout problem, the assignment of tasks and the routing problem is required.

The content of clusters 2 and 4 is not observed in the main path, but represent relevant contributions to the layout design of RMS. Papers within cluster 2 emphasise the need to consider RMS core characteristics for selecting layout configurations. Each of the six core characteristics cited by the majority of authors may impact on the layout of the manufacturing system, to a lesser or greater extent. These characteristics reduce the time and effort of reconfiguration, and consequently enhance the system's responsiveness. They can reliably reduce lifetime cost by enabling a system to change constantly during its lifetime, despite changes in markets, consumer demand and process technology (Koren and Shpitalni, 2010). Therefore, the core characteristics and the layout design cannot be dissociated, because the ultimate goal of RMS is to achieve reconfigurability. This conclusion is coherent with previous research, which argues that in a basic design phase, the designer should decide the degree, type and level of reconfigurability, *i.e.* of each core characteristic, that will be emphasised and implemented in the advanced design phase, that deals with the detailed design of the system, in terms of logical and physical aspects (Andersen et al., 2017). Modularity can provide an adjustable, modular and reconfigurable structure to machines, promote the re-use and exchange of a system's components, allow the introduction of new technologies rapidly and encourage more reconfigurable facilities, thus contributing to the layout design (Benderbal et al., 2018b). Integrability reduces the effort needed to integrate new components and additional modules of machines and/or layouts (Unglert et al., 2016c). Therefore, modularity and integrability enable a cost effective layout design (Koren et al., 2018). Customisation implies that the layout design is directed at producing a part/product family (Koren and Shpitalni, 2010). Convertibility and scalability act at system and machine levels. At the system level, machines can be added or removed; at the machine level, specific changes can be applied to machine axes or by adding spindles (Koren and Shpitalni, 2010; Renzi et al., 2014). Diagnosability is an important core characteristic that reduces the ramp-up time when altering the layout configuration. Nevertheless, this characteristic is mostly related to the control system's specifications in the RMS design process, since it relies on the diagnosis of a system's current state, in terms of quality and reliability. This explains the small number of papers that address diagnosability in the context of layout design of RMS (Bruccoleri et al., 2005).

Papers within cluster 4 indicate that meta-heuristic techniques, *e.g.* PSO, GA and ACO, have been widely applied to the layout design of manufacturing systems. These results are in accordance with those provided by the papers of the main path and cluster 3. Meta-heuristic techniques have been efficient tools for solving combinatorial optimisation problems like those found in DMS and FMS design (Renzi et al., 2014). Among these methods, GA seems to be the most commonly used (Dahane and Benyoucef, 2016; Dou et al., 2008; Kant et al., 2017; Maniraj et al., 2017). Nevertheless, these works that rely on GA for optimising the layout design of systems seldom justify the choice of the optimisation method, therefore it seems that the preference given to GA may only be due to historical reasons or to the trend of the moment (Renzi et al., 2014).

The results of this research show that the layout design of RMS can be addressed considering four perspectives (Figure 5.5), highlighted by the cluster analysis:

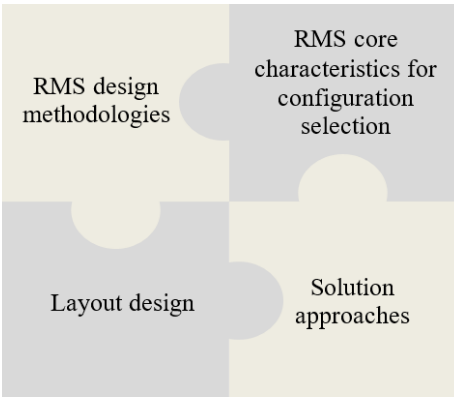


Figure 5.5: The four perspectives identified in the literature review.

1. **RMS design methodologies**. The layout design is considered within the RMS design process, which includes the relationship of the layout design with other dimensions of RMS, such as material handling systems' design/selection and control system specification, or the positioning of the layout design within a framework to design RMS.

2. **RMS core characteristics for configuration selection**. The different core characteristics are considered in the layout design of RMS and are used to evaluate the reconfigurability of manufacturing systems.

3. **Layout design**. This perspective considers the process to model the layout design, taking into account the choice of machines and the layout problem.

4. **Solution approaches**. This is strongly related to the previous perspective, dealing with the development of effective approaches to solve the layout design of RMS.

5.5 Future research directions

Research challenges exist in each of the four perspectives identified in this investigation. Regarding the perspective of RMS design methodologies, future research could consider standardising terminologies, the number of phases in the design methodology and the level of detail in each of them. These studies should also consider that design methods for conventional manufacturing systems do not support RMS design, thus, there is a need to adapt existing methods and/or develop new ones to cope with the layout design of RMS. Technologies provided by Industry 4.0 must be considered in the design of layouts for RMS since they provide tools to achieve smart layout design.

In respect to RMS core characteristics for configuration selection, it is essential to understand the impact of each one on the layout design. Therefore, further research may address empirical studies to analyse which core characteristics effectively affect the layout design of RMS and to what extent. Moreover, the impact of the core characteristics on the quality, responsiveness and operational performance of the manufacturing system layout are relevant topics for future investigation.

However, it seems that there is no consensus regarding the core characteristics of RMS. Most authors refer to the six core characteristics defined by (Koren and Shpitalni, 2010), but agility, commonality, compatibility and reusability are also mentioned (Hasan et al., 2012b; Galan et al., 2007). More recently, studies addressing RMS design for sustainability have gained visibility (Aljuneidi and Bulgak, 2016; Singh et al., 2017). Furthermore, an empirical investigation has posited the existence of five core characteristics, which is supported by the earliest studies on RMS (Maganha et al., 2018; Renzi et al., 2014; Abdi and Labib, 2003). Therefore, it would be advisable to increase the research in this area to identify which are, indeed, the core characteristics that provide reconfigurability to manufacturing systems and layouts. After being identified, it would be opportune to explore the degree of implementation of each core characteristic to complement the results of this literature investigation. Exploratory survey research in manufacturing companies would be beneficial in this sense, especially in different production environments, to identify the ways in which the core characteristics are implemented in the industrial community.

The configuration selection of RMS according to the core characteristics also raises other interesting considerations in terms of research questions in the field of layout design. How do the core characteristics of reconfigurability work together? Are there core characteristics that, when improved, automatically improve other characteristics? Or, are there core characteristics with the opposite behaviour that, when improved, impact negatively on another characteristic? Does achieving reconfigurability in different production environments or system typologies imply different behaviour of the core characteristics?

The layout design is a concern that embraces all types of production systems, including cellular manufacturing systems, flow shops, assembly lines and job shops. Nevertheless, none of the studies identified investigated the relationship between a system's typology and the need for reconfigurability. Future efforts are required to establish this relationship and the advantages, disadvantages and the ease of layout reconfiguration in each system type, as well as whether the approach to achieve reconfigurable systems and/or layouts should be based on the typology of the system and whether the approach to provide reconfigurability for each type of system is the same. These further efforts may be capable of identifying whether there is a more favourable manufacturing environment for reconfigurability or if all environments benefit from reconfigurability in the same manner.

The layout design represents key research challenges, such as how the initial layout of an RMS should be designed in order to facilitate the layout reconfiguration and what is the trigger for the re-layout of a manufacturing system. Identifying and expressing the need for change in a system's lifetime has been overlooked in the literature, even though it is, potentially, one of the most critical tasks in practice (Andersen et al., 2017). Previous studies argue that the re-layout may be triggered by reasonable changes in the factors that affect the performance of the current layout, *e.g.* product mix and volume (Meng et al., 2004), but also by economic criteria (Singh et al., 2017). Nevertheless, there is very little investigation focusing on these problems, thus future studies at this level might concern the limitations of the tools to apply to the layout design of RMS, the lack of supportive tools in the RMS design process and to support the decision of how and when to reconfigure the manufacturing system (Andersen et al., 2017).

Furthermore, measures such as the core characteristics, costs, investments and cycle times have been considered to select machines among an available set and to evaluate the performance of the layout configuration. Future investigation may develop the studies concerning performance measures to evaluate layout configurations in RMS further, to hopefully identify which indicators are often considered and how they are used. Other classical measures, such as makespan, WIP and throughput, might also be considered.

Further research opportunities regarding solution approaches may be directed at the adoption of optimisation combined with simulation (Bortolini et al., 2018). Simulation optimisation techniques are an effective way to design facility layout (Wang et al., 2008). This technique is widespread in the literature since the output of the simulation is used by the optimisation module to provide feedback on the progress of the search for an optimal solution (Bensmaine et al., 2013; Bortolini et al., 2018). Simulation models have been connected to evolutionary methods to evaluate candidate layout solutions, taking into account the system's performance in a more realistic way (Renzi et al., 2014).

Other methods, *e.g.* simulated annealing (SA), should be exploited in future investigations, broadening the existing literature, since previous studies have shown that SA may find better solutions than GA and TS in less computational time (Rabbani et al., 2014). Indeed, the literature dedicated to optimisation methods expresses the good performance and efficiency of SA in discrete environments, even though their applications are but a few

(Renzi et al., 2014). Hybrid approaches also deserve more investigation, since they have been successfully applied to the design of DMS and FMS. Hybrid methods combine several algorithms trying to exploit the features of each one better to enhance the optimisation process overall. The combination of GA or SA to a local search algorithm allows a broad exploration of the design space at first, followed by a quick fine-tuning of the optimum solution found. Also, when the complexity of the problem is large, the combination of meta-heuristic models and search algorithms can ease the quest for an optimum solution (Renzi et al., 2014). Additionally, the introduction of multi-objective meta-heuristic techniques may efficiently solve larger real size instances (Bensmaine et al., 2013; Bortolini et al., 2018). The research challenges discussed are summarised in Table 5.3.

Table 5.3: Insights concerning future research challenges.

Perspectives	Research challenges
RMS design methodologies	Standardise terminologies, the number of phases in the design methodology and the level of detail in each Adapt design methods of conventional manufacturing systems and/or create new ones to cope with the layout design of RMS
RMS core characteristics for configuration selection	Understand the impact of each of the core characteristics in the layout design of RMS Identify which are, indeed, the core characteristics that can provide reconfigurability to manufacturing systems and layouts Investigate empirically which characteristics effectively affect the layout design and to what extent Identify which are, indeed, the core characteristics that can provide reconfigurability to manufacturing systems and layouts Investigate how the core characteristics behave in relation to each other in the context of layout design of RMS Establish the relationship between core characteristics and different business production strategies
Layout design	Understand how the initial layout of an RMS should be designed to facilitate the layout reconfiguration Identify what triggers the need for the re-layout of a manufacturing system Develop tools to support the decision of how and when to reconfigure the layout of RMS Combine reconfigurability, layout design and technologies provided by the Industry 4.0 paradigm Develop studies on performance measures to evaluate layout configurations in RMS
Solution approaches	Explore the use of simulation optimisation to face the uncertainties of the layout design Explore other meta-heuristic solution methods, such as SA and hybrid approaches

5.6 Conclusions

The aim of this chapter was to rationalise and systematise the existing scientific literature on the layout design of RMS. Different quantitative bibliometric analyses have been carried out, relying on algorithms and software tools that allowed a dynamic representation of the flow of knowledge development over time. The main path analysis demonstrated that the complexity of the problems studied has increased over the years. Four clusters were identified in the co-occurrence analysis of authors' keywords, providing a more complete picture of the knowledge on this topic that identifies the main research trajectories. The results of these analyses are all in accordance, emphasising a trend to investigate four main perspectives: RMS design methodologies, RMS core characteristics for configuration selection, layout design and solution approaches. The findings also highlight the increasing interest in layout problems in the context of RMS as well as the use of meta-heuristic techniques in layout design. The dynamic analysis highlighted critical areas and emerging topics that are underrepresented and require further investigation.

This research focused on an SLNA analysis to identify trends, evolutionary trajectories and key issues that have influenced the research on layout design of RMS. The limitations of this methodology originate from the fact that only considering citations concerning the analysis may not be completely informative about the real contribution of a paper. Studies tend to cite papers of well-known researchers, which have already received a high number of citations, because they are seen as reliable sources of information due to their reputation and popularity.

Additional material related to this chapter, which has not been considered for the submitted article, is provided in the Appendix B. This material includes a theoretical background of the layout problem of RMS. This work was presented at the *27th International Conference on Flexible Automation and Intelligent Manufacturing* (FAIM2017).

Part IV Case study

Contents

Chapter 6 Leveraging the reconfigurability of assembly lines through mobile collaborative robots

Abstract

Disruptive technologies promoted by the Industry 4.0 paradigm, such as collaborative robotics, attempt to support the reconfigurability of manufacturing systems and to contribute to adaptive operational conditions. In addition to that, new technological advances promote data capture and share to facilitate rapid and accurate decision-making in MH-RMS, where tasks can be split between humans and mobile robots. The objective of this chapter is to analyse the potential of collaborative robotics in leveraging the reconfigurability of assembly lines. To achieve this, a model-based hybrid optimisation approach is proposed to solve scheduling and layout problems. The results show the impacts of the introduction of mobile robots on assembly lines, in particular situations of varying product mix and demand volume. The findings highlight some advantages and drawbacks of introducing mobile collaborative robotics, aiming at leveraging the reconfigurability of assembly lines.

6.1 Introduction

Manufacturing systems face a volatile demand with varying customer needs in terms of volume and product mix (Beauville et al., 2019). Thus, they must be increasingly reconfigurable to react to these variations in a rapid and cost-effective manner (Koren et al., 2016). The Industry 4.0 paradigm holds the promise of increased flexibility and speed, mass customisation, improved quality and enhanced productivity in manufacturing, enabling companies to deal with many challenges, such as increasingly individualised products, shortened response time to market and high product quality (Zheng et al., 2018). In this context, RMS have been widely acknowledged as suitable for handling situations where responsiveness and productivity are of vital importance. Indeed, this type of system can provide a way to achieve a rapid and adaptive response to changes in demand volume and product mix (Leitao et al., 2012). The design for rapid changes through the ability to repeatedly modify the capacity and functionality is enabled by reconfigurability, which allow for the cost-efficient reuse and prolonged lifetime of manufacturing systems (Andersen et al., 2017).

In order to enable reconfigurability, manufacturing companies must implement some core characteristics, such as modularity, integrability, diagnosability, adaptability and customisation. These characteristics facilitate the design of manufacturing systems to be reconfigurable, using hardware and software modules that can be integrated in a quick and reliable manner. They also allow achieving the system's functionality and scalability required for the production of several product families. Without them, the reconfiguration process will be lengthy or even impracticable (Koren et al., 1999).

Manufacturing systems' reconfiguration activities can be classified into two types: soft and hard. Soft (or logical) reconfiguration activities include re-programming of machines, re-planning, re-scheduling, re-routing and increasing/decreasing the number of shifts or workers. Hard (or physical) reconfiguration activities include adding or removing machines/modules and changing material handling systems (Youssef and ElMaraghy, 2006). Although these are active research topics in the field of RMS, these issues need to be studied under the Industry 4.0 paradigm (Mosallaeipour et al., 2018; Nejad et al., 2018; Benderbal et al., 2018a, 2017b; Bensmaine et al., 2014; Yan et al., 2018). Particularly, more attention should be given to the scheduling and the layout design of RMS, considering the introduction of novel technologies, such as mobile collaborative robots. New modelling approaches should be developed to better understand how robotic technologies can be used to design and run RMS. Many research works have focused on the design of RMS through the core characteristics of reconfigurability (Singh et al., 2007; Li et al., 2007). Even though they highlight that the novel technologies endorsed by Industry 4.0 paradigm might contribute to the improvement of the reconfigurability, studies that address the relationship between the introduction of these novel technologies in actual manufacturing systems and reconfigurability are still lacking (Maganha et al., 2018; Cohen et al., 2017; Bortolini et al., 2017).

This chapter is focused on topics that might strongly influence the future design and operation of hybrid production systems. The main objective is to analyse the potential of collaborative robotics in leveraging the reconfigurability of assembly systems. To do so, a hybrid optimisation approach is proposed to solve scheduling and layout problems in reconfigurable assembly lines, where tasks can be divided between humans and mobile collaborative robots that share the same workstation. The results given by the optimisation approach are analysed and compared with the core characteristics of reconfigurability.

The remainder of this chapter is organised as follows. Section 6.2 discusses the concept of RMS and some existing works on scheduling and layout problems in this context. Section 6.3 describes with more detail the problem addressed. Section 6.4 presents the proposed solution approach. The results are presented in Section 6.5 and discussed in Section 6.6. Section 6.7 presents some final remarks and future research work.

6.2 Literature review

6.2.1 Reconfigurable manufacturing systems

The concept of RMS had emerged due to the need of manufacturing companies respond to rapid changes in process technology, launch of new products, integration of new functions, and fluctuations in product mix and demand volume (Koren et al., 1999; Mehrabi et al., 2000a). RMS have a changeable structure that can provide high throughput and high flexibility, allowing a quick and efficient reaction to market changes (Bortolini et al., 2018). In this context, RAS are integrated computer-controlled systems of assembly robots, automated guided vehicles and buffers that can be used to assemble a variety of similar product types, which provides flexibility for a particular product family (Yu et al., 2003). One main feature of RAS is the variable capacity and functionality (Cohen et al., 2017). Similarly to RMS, RAS can dynamically respond to internal and external changes by reconfiguring its physical structure (hardware) and system controls (software). At the physical level, the configuration of RAS is scalable and easy to expand. The system can add/remove assembly devices to/from a system by "Plug and Produce" architecture. At the system control level, the RAS shows its abilities of intelligence and autonomy (Arai et al., 2000). In order to realise RAS, companies must implement reconfigurability, which is essential to meet the current challenges of designing manufacturing systems that should be able to produce multiple product variants within a product family and that have changeable functionality and capacity (Napoleone et al., 2018).

Reconfigurability is enabled by core characteristics, such as modularity, integrability, diagnosability, customisation and adaptability (Maganha et al., 2018). These characteristics enhance systems' responsiveness (Koren, 2013). *Modularity* provides more adjustable manufacturing resources that can be rearranged in a straightforward way. In short, modularity promotes the exchange and re-use of system's components, simplifies outsourcing, helps the introduction of new technologies, and encourages a more flexible allocation of resources (Benderbal et al., 2018b). *Integrability*, in turn, allows the ready integration of the available resources. To achieve this, the manufacturing system should be designed with mechanical, informational and control interfaces that facilitate the communication amongst the resources (Koren and Shpitalni, 2010). For those reasons, modularity and integrability are critical core characteristics when manufacturing systems require frequent layout modifications.

In environments where reconfiguration occurs more often, it is essential to rapidly tune the reconfigured system so that it can start production immediately and without quality problems. In this case, *diagnosability* enables the fast detection of quality problems after reconfiguration, contributing to the reduction of the ramp-up time (Andersen et al., 2016). In sum, modularity, integrability, and diagnosability help reconfiguring manufacturing systems efficiently, in terms of effort and time (Benderbal et al., 2018b). The next core characteristic is *customisation*, which has two main features: customised control and flexibility. The customised control consists in providing the exact control functions needed. The customised flexibility means that the manufacturing system has enough flexibility to produce a product family and offer a fast throughput and higher production rates. This increases the process variety needed for the production (*e.g.* various machines, tools, modules, tasks and configurations) (Benderbal et al., 2018b). Thereby, it can help manufacturing companies to respond to fluctuations on product mix. Finally, *adaptability* allows the modification of production functionality and capacity. The functionality can be transformed by changing system's components (*e.g.* fixtures, tools or modules) to switch quickly from the manufacture of a certain product to another one. The capacity, on the other hand, can be changed by adding or removing resources of the manufacturing systems (Koren and Shpitalni, 2010). In addition to that, diagnosability and adaptability complement each other, because scaling-up systems requires a subsequent ramp-up period that can be reduced dramatically by implementing diagnosability (Koren, 2013).

Several researchers have addressed the design of RMS (Koren et al., 2016; Rabbani et al., 2014; Lee and Tilbury, 2007; Padayachee and Bright, 2014; Niroomand et al., 2014; Abbasi and Houshmand, 2011; Bruccoleri et al., 2005). These works state that the effectiveness of these systems depends on implementing the core characteristics in the design and utilisation stage. Other works addressed RMS configurations from an evaluation perspective (Singh et al., 2007; Li et al., 2007). Despite the significant progress made in this field, there is a lack of methodologies that drive companies in the transition towards the implementation of the core characteristics of reconfigurability (Andersen et al., 2018a; Bortolini et al., 2018).

The novel technologies promoted by the Industry 4.0 paradigm, such as big data, internet of things, real-time optimisation and mobile collaborative robotics, might significantly contribute to enhance the reconfigurability of manufacturing systems (Maganha et al., 2018). Cohen et al. (2017) have proposed a general architecture of introducing Industry 4.0 principles in existing flexible assembly lines. Bortolini et al. (2017) have investigated the impact of Industry 4.0 principles on the design of assembly lines. These studies show that Industry 4.0 technologies can actually promote the reconfigurability of manufacturing systems, analysing what should change due to this new paradigm. However, neither of them has exploited the integration of reconfigurability together with these novel technologies. There is a major gap in the research that lies in the study of the impacts of combining reconfigurability and the introduction of Industry 4.0 technologies. Moreover, although these existing works have proposed frameworks for analysing how the transformations due to the Industry 4.0 paradigm are expected to occur, the analysis of the introduction of the novel technologies in actual manufacturing systems is very restricted. Indeed, further research is required to investigate specific Industry 4.0 enabling technologies in these domains (Bortolini et al., 2017). This chapter is aimed at analysing an important issue in this regard, namely the impacts of the introduction of mobile collaborative robots on the leverage of the reconfigurability of assembly lines.

6.2.2 Planning and scheduling problems in RMS

Literature dealing with RMS is rich and covers many areas such as process planning and production scheduling (Bensmaine et al., 2014). The process planning is the link between design and manufacturing. It specifies what components are needed to manufacture a product and which operations are required to transform those components into final products. The outcome of process planning includes the information for manufacturing operations and their parameters, as well as the identification of the resources requested to perform these operations (Bensmaine et al., 2012). Azab and Elmaraghy (2007) have considered the reconfiguration of an existing process plan, in order to meet new production requirements. Azab et al. (2007) have proposed a new heuristic based on simulated annealing to sequence a set of machining operations in order to minimise the total idle time, subject to precedence constraints. Bensmaine et al. (2011, 2012) have dealt with the generation of process plans. In Bensmaine et al. (2011), the authors have developed a simulation-based NSGA-II approach for a multi-unit single-product type. They have established a multi-unit macro-level process plan to perform different parts/operations on several machines, in which the process plan is associated to each unit. In Bensmaine et al. (2012), the authors have adapted a AMOSA meta-heuristic to generate a set of process plan solutions, based on completion time, total cost and reconfiguration effort. They elaborated an experimental comparison based on the results obtained, classifying them in a preferential order using TOPSIS.

Scheduling is a function of manufacturing systems that is intended to assign resources to the operations indicated in the process plan, meeting criteria such as due date and makespan. Despite the strong relation between process planning and scheduling, conventionally, they are studied separately. In practice, they are performed separately as well (Bensmaine et al., 2012). Recent works have proposed solution approaches to solve scheduling problems in RMS. Li and Xie (2006) have applied a GA embedded with extended time-placed Petri nets (ETPN) for systems scheduling, aiming to optimise reconfiguration costs and balanced production. Galan (2008) has proposed a meta-heuristic approach to group products into families and then schedule these families, minimising the total cost. Valente and Carpanzano (2011) have developed a dynamic algorithm to schedule automation tasks over time. The objective was to determine the sequence of automation tasks to be executed in order to optimise the resource utilisation considering deadline constraints. Nehzati et al. (2012) have used a fuzzy-based scheduling model to deal with the job assignment problem. Azab and Naderi (2015) have considered the problem of scheduling jobs. The authors applied a mixed integer linear programming (MILP) model, in order to determine the configuration and job sequence to minimise makespan. Hybrid optimisation approaches have been also used to solve this problem (Li and Xie, 2006; Azab and Naderi, 2015; Prasad and Jayswal, 2018).

Recent advances in mobile collaborative robotics allow the sharing of tasks between humans and mobile robots at the same workstation. This has led some researchers to consider the production scheduling problem when robot resources are available. Giordani et al. (2009) have proposed a decentralised MAS to solve scheduling problems where production resources are assumed to be mobile units. The results included the assignment of robots to the respective tasks with the objective of minimising production costs given the product demand rates during the planning time horizon. Mosallaeipour et al. (2018) have dealt with the problem of robots scheduling in flexible manufacturing cells. They have developed a decision-making framework to select the most appropriated scheduling scheme, which employs the accurate robot scheduling strategies and avoids possible errors. The outcomes have provided optimised time and costs of the schedule. Nejad et al. (2018) have studied the scheduling problem in a flexible robotic cell, aiming to determine the order of the robots' actions that minimises the cycle time. They have proposed a simulated annealing algorithm to solve large-size problems. Yan et al. (2018) have investigated a real-time dynamic job-shop scheduling problem in a robotic cell, in which multiple jobs enter into the cell with unexpected arriving dates. The problem was formulated as a MIP model and they have proposed an exact iterative algorithm to solve it. Vieira et al. (2018) have studied flexible manufacturing systems with mobile robotic resources. They have proposed a simulation-optimisation methodology to provide an optimal production schedule regarding line efficiency and the number of robotic resources required. Nevertheless, despite these relevant contributions, there is a dearth of literature considering manufacturing environments where robots collaborate with human workers. This highlights the need of more research, considering the integration of robots' assistance, in planning and scheduling problems of manufacturing systems (Giordani et al., 2009).

6.2.3 Layout problems in RMS

In recent years, studies have highlighted the need to design more flexible, modular and reconfigurable layouts for dynamic and uncertain environments (Maganha and Silva, 2017). Indeed, the research on the layout design of RMS has gained attention due to the degree of uncertainty and unpredictability that characterise companies, which need a high level of responsiveness to changes (Benderbal et al., 2018b). The layout design includes the choice of machines and the layout of the manufacturing system. The choice of machines is related to the selection of machines to be included in the layout. The layout of the manufacturing system concerns the layout problem, which is the assignment of the machines selected to their locations (Oke et al., 2011).

Considering the operational aspects of RMS design along with layout is a complex task (Benderbal et al., 2018a). It needs to take into consideration not only the current product to be manufactured and classical constraint (*e.g.* precedence relation), but also the specificity of RMS, the whole product family and the transition that may occur when switching from one product to another in this product family (Benderbal et al., 2017b). RMS undergo frequent configuration changes to adapt to different production requirements. To raise efficiency and to reduce manufacturing cost, the layout should be redesigned and reconfigured frequently as well (Guan et al., 2012). Moreover, the layout problem is an NP-complete problem, which is very difficult to solve (Drira et al., 2007).

Despite its complexity, many authors have sought to address the layout problem of RMS. Xiaobo et al. (2000b) have proposed a stochastic model to select the optimal configuration for product families so as to maximise an average profit. Kuo (2001) have argued that to construct a high performance manufacturing system, the allocation of resources must be analysed first. To do so, the author has proposed an ELAA to find the near optimal equipment layout in order to reduce the cycle time of core products. Yamada et al. (2003) have applied PSO to optimise the layout of a manufacturing cell and the allocation of transport robots in a system composed of transport robots, input stations, output stations, movable manufacturing cells and objects to process. Meng et al. (2004) have stated that the layout problem in RMS differs from traditional, robust and dynamic layout problems in two aspects: i) it assumes that production data are available only for the current and upcoming production period; and ii) it considers queuing performance measures (*e.g.* work in progress inventory and product lead time) in the objective function. They have proposed an open queuing network-based analytical model to estimate the stochastic performance of a layout. Purnomo and Wiwoho (2016) and Azevedo et al. (2013, 2016, 2017) have applied MIP to solve a multi-facility layout problem. The first have considered minimising material handling costs and re-layout costs and maximising closeness rating. The second have targeted the minimisation of material handling costs (inside and between facilities) and re-layout costs, the minimisation of the unsuitability of department positions and locations, and the maximisation of adjacency between departments. A general simulation framework was also proposed by Cedeno-Campos et al. (2013) and Zheng et al. (2013), in order to provide the outputs of the layouts and costs, as well as to analyse the benefits and performance of RMS, based on the variation of products, quantity and order lead time.

Among these contributions, there is very little research that consider manufacturing environments where the resources are assumed to be mobile. There is a lack of studies that cope with the Industry 4.0 paradigm, in which mobile collaborative robots can dynamically change their work position to increment the product rate of different typologies of products in respect to the fluctuations of the demands and production costs during a given time horizon (Giordani et al., 2009). Furthermore, the use of hybrid optimisation approaches to deal with the layout problem in RMS is also limited.

6.2.4 Final remarks

Although reconfigurability has been widely studied in the context of RMS, there is a gap between the literature and practice that makes it difficult to practitioners to implement the reconfigurability in actual systems. In the literature, there are various contributions to the design of RMS, focusing on the core characteristics of reconfigurability. Nevertheless, the implementation of reconfigurability, *i.e.* of its core characteristics, is in an initial stage, as well as the deployment of RMS (Maganha et al., 2018). This may occur due to the limited empirical focus of researchers, that neglect how reconfigurability can be realised in real design solutions (Andersen et al., 2018a). Therefore, it is of the foremost interest of both, academics and practitioners, to fulfil this existing gap between theory and practice.

In addition, the planning, scheduling and layout of RMS have been investigated in the scientific literature during the last two decades. Planning and scheduling problems in Industry 4.0 environments may include the sequencing of jobs and tasks assignment of collaborative resources. Furthermore, the resources are assumed to be mobile units, thus the layout problem must consider the allocation of resources that can dynamically change their position during a planning horizon. In order to solve these problems, existing approaches should be adapted or new methods should be developed (Zheng et al., 2018).

Finally, it is important to analyse the impacts of the integration of reconfigurability and novel technologies provided by the Industry 4.0 paradigm, and its implications to scheduling and layout problems. Particularly, how the reconfigurability can be realised in real manufacturing systems by using collaborative robotics and how this specific enabling technology of Industry 4.0 might impact on scheduling and layout problems. In this regard, the existing works are mostly conceptual, considering what aspects and how they are expected to change on manufacturing due to the Industry 4.0 paradigm. Therefore, these issues need to be addressed in case studies of real manufacturing companies, to fulfil the gap between theory and practice.

The foremost contribution of this chapter relies on an analysis of the potential of collaborative robotics technologies in leveraging the reconfigurability of assembly systems. To achieve this objective, a model-based hybrid optimisation approach is proposed to solve scheduling and layout problems in assembly lines, considering aspects of dynamic capacity, *i.e.* mobile robots, and fluctuations on product mix and demand volume. The results of the optimisation approach are discussed and compared with the findings of reconfigurable assembly lines. The advantages of analysing these issues together consists in characterising and generalising some relevant sequencing, lot sizing and allocation decisions that affect the performance of assembly lines, under the Industry 4.0 paradigm.

6.3 Case study

6.3.1 Problem description

The problem presented has been motivated by a company that assembles two different types of products (A and B). The products are assembled in a reconfigurable line composed of three workstations and mobile collaborative robots that can move among the workstations whenever required. One product is allowed at a workstation at a time. The assembly of the products requires the execution of a set of tasks, each one with a given processing time and precedence constraints. Both product types have tasks that are performed by human resources or mobile robots. Tasks performed by humans are common to both products, while tasks performed by robots are specific to each product type. There is one human resource at each workstation that performs all the common tasks. The specific tasks are performed by multitasking mobile robots that can coexist with humans at the workstations. Both products follow the same assembly sequence, that starts at workstation (WS) 1. Once all the tasks that need to be performed at a workstation are concluded, products can move forward. After completion of all assembly tasks, the products are sent to the warehouse (WH). The products' flow and the sequence of workstations are presented in Figure 6.1.

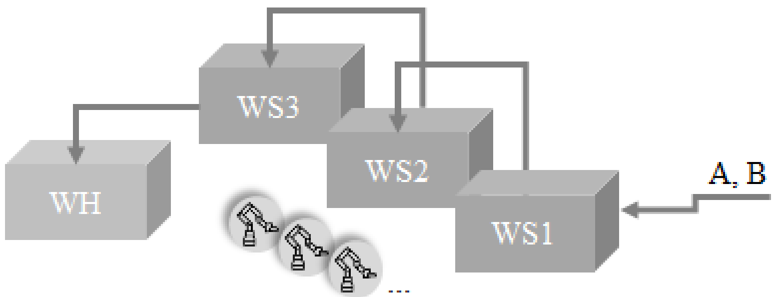


Figure 6.1: Products' flow and sequence of workstations in the assembly line.

The robots are assigned to the specific tasks according to their availability and the robots' displacement time among workstations is considered negligible. A workstation can have more than one robot at a time. Nevertheless, a robot cannot perform more than one task at a time and pre-emption is not allowed.

The tasks required for the assembly of the two types of products are presented in Table 6.1, together with their respective workstation, processing time and precedence. While the human resource is performing the common tasks, one or more collaborative robots are called to the workstation to perform, in parallel, the specific tasks of products. For instance, at WS2, the set of common tasks is composed by Task_102a and Task_102b. Task_102a has a processing time of 13.2s. After the completion of Task_102a, a robot is called to perform Task_13, while the human resource at that workstation can initiate the execution of Task_102b simultaneously. The same operating logic is applied to the other workstations.

The set of tasks allocated to human resources at each workstation have a common total processing time (30s), corresponding to the assembly line cycle time desired.

Table 6.1: Data of tasks to be performed for both types of products.

Product	Workstation	Task_ID	Task type	Processing time (s)	Precedent task
A	1	Task_100	Common	30.60	
		Task_1	Specific	9.0	
		Task_2	Specific	3.0	Task_1
		Task_3	Specific	6.0	Task_1
		Task_5	Specific	1.8	Task_3
	2	Task_102a	Common	13.2	
		Task_102b	Common	16.8	
		Task_7	Specific	4.2	
		Task_8	Specific	7.2	
		Task_9	Specific	3.0	
		Task_12	Specific	3.0	
		Task_13	Specific	6.6	Task_12, Task_102a
	3	Task_104a	Common	1.8	
		Task_104b	Common	21.0	
		Task_104c	Common	7.2	
		Task_16	Specific	6.0	
		Task_17	Specific	6.0	
		Task_19	Specific	6.0	Task_104a
		Task_18	Specific	3.0	Task_104a, Task_104b
B	1	Task_101	Common	30.0	
		Task_4	Specific	4.8	
		Task_21	Specific	7.2	
		Task_22	Specific	7.2	
		Task_23	Specific	7.2	Task_21, Task_22
		Task_24	Specific	7.2	Task_21, Task_22
		Task_25	Specific	9.0	Task_23, Task_24
	2	Task_103	Common	30.0	
	1	Task_105	Common	30.0	
		Task_26	Specific	15.6	
		Task_27	Specific	9.0	

The objective is to minimise the number of robots required to achieve the cycle time desired, while determining: i) the sequence of assembly of all products, ii) the task assignment to the robots, and iii) the allocation of the robots to the workstations.

Finally, it is relevant to discuss the main characteristics of this RAS. First, this assembly line was designed to provide *customised flexibility* to run with a product family. Second, robots can move among workstations. Thereby *modularity* is present in the system, due to the capability of re-utilisation of the robots according to the workstation's task requirements. Third, robots can also change their functionality in order to perform many different tasks, of both types of products, and shift their capacity to where it is needed. This shows the ability of the assembly line to adapt its functionality and capacity by means of an adjustable structure, which characterises the existence of the *adaptability*. Fourth, to move from a workstation to another one, robots must be able to identify what tasks should be performed to adjust their function and go to where their skills are required. Thus, the *integrability* is also implemented in this assembly system, allowing the communication among the robots. All these features distinguish this assembly line as a RAS that combines reconfigurability and mobile collaborative robotics.

6.4 Proposed approach

The proposed hybrid optimisation approach uses a meta-heuristic and a list algorithm. The iterative procedure of the method is illustrated in Figure 6.2. A single solution based meta-heuristic or a population based meta-heuristic can be used. For single solution based meta-heuristics, the neighbourhood system is a permutation of jobs. In this study, two single solution based meta-heuristics were chosen: stochastic descent and simulated annealing (section 6.4.2). The main objective was to obtain results rapidly in order to evaluate the suitability of the proposed hybrid optimisation approach to solve the scheduling and layout problems in reconfigurable assembly lines. Therefore, these meta-heuristics were chosen, because they were already implemented in previous research, consequently, speeding up the development process (Silva and Klement, 2017).

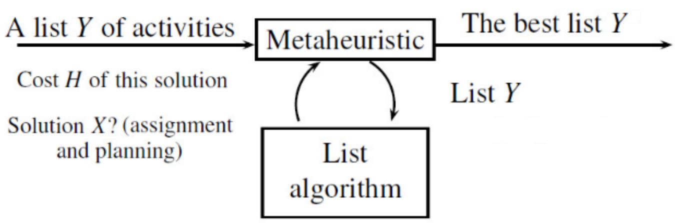


Figure 6.2: Hybridisation of a meta-heuristic and a list algorithm.

The encoding used by the meta-heuristic is a list Y of jobs. The list algorithm considers the jobs in the list order and assign their tasks to the required mobile robot, respecting the problem constraints. This builds the solution X. The objective function H evaluates the solution X. According to this evaluation, the solution is chosen or not by the meta-heuristic. At the end of the running, the solution given by the hybridisation is the best list, *i.e.* the best sequence of jobs: the one that optimises the objective function by applying the list algorithm (Silva et al., 2018).

This hybridisation can be used to solve many problems, because the specificity of a given problem is only considered in the list algorithm. Several tactical and operational problems have already been solved with this hybrid optimisation approach. Silva et al. (2016) have solved a real-world lot-sizing and scheduling problem from a plastic injection company. The objective was to allocate jobs to each available machine and define the processing sequence in each machine in order to minimise the total tardiness. Klement et al. (2017a) have dealt with an optimisation problem of a hospital system, in which the objective was to assign the exams to human and material resources during a period. In this problem, some material resources are located at different places and human resources have specific competences on these material resources. Silva and Klement (2017) have solved a multi-period job-shop scheduling problem, in which the objective was to define the operations sequence in each machine in order to minimise the total penalty. Mazar et al. (2018) have applied this hybrid approach in order to optimise the robotised treatment of plants' diseases in a greenhouse. The optimisation aim is to minimise the number of robots' missions required during a limited period of time, while ensuring the treatment of all infected plant in the greenhouse. These previous works demonstrate that the proposed approach can be adapted to several problems variants (Silva and Klement, 2017).

6.4.1 A list Y of jobs

The general scheme of the encoding is given by Equation 6.1, with Ω the set of all lists Y and S the set of all admissible solutions X built by the list algorithm L. Ω is the set of all permutations of jobs (Klement et al., 2017b). Cardinal of Ω is given by Equation 6.2 with k the different types of products and n the number of jobs. $Y \in \Omega$ is a list of jobs. More details about the encoding are given in Gourgand et al. (2014).

$$Y \in \Omega \xrightarrow{\text{Heuristic L}} L(X) = X \in S \xrightarrow{\text{Criterion H}} H(X) \tag{6.1}$$

$$C_{n,k} = \frac{n!}{k!(n-k)!} \tag{6.2}$$

6.4.2 Meta-heuristic

The meta-heuristic performs in Ω. An initial solution is randomly generated, *i.e.* a list of jobs (A and B) is randomly sorted between one and the number of jobs to be assembled. A neighbourhood system is used to visit the set of solutions, allowing to switch from one solution to another. The neighbourhood system V is a permutation of two jobs in the list Y. The job at the position i permutes with the job at position j, with i and j two different random numbers (Klement et al., 2017b). In this particular case, the permutation only occurs if the job at the position i is different from the job at the position j.

Stochastic descent

The stochastic descent is one of the oldest meta-heuristics. Its principle consists in generating a solution X' close to a current solution X, according to the neighbourhood system V. This principle is represented in Algorithm 1. If the objective function $H(X')$ is less than or equal to $H(X)$, the solution X' is accepted. This method is a simple descent that converges to a local minimum. It uses a stochastic exploration mechanism, in which the neighbour X' is chosen uniformly and randomly in $V(X)$. The advantage of using the stochastic descent relies on its simplicity and speed. However, the results obtained tend to present poor quality (Klement, 2014).

Algorithm 1 Principle of the stochastic descent algorithm.

Input: initial solution X
1: **while** the stop criterion is not reached **do**
2: Choose uniformly and randomly $X' \in V(X)$
3: **if** $H(X') \leq H(X)$ **then**
4: $X = X'$

Simulated annealing

The simulated annealing is inspired by a process used in metallurgy that consists of alternating cycles of slow cooling and heating. Applied to the optimisation field, it consists in executing a descent with a non-zero probability to choose a worst solution than the current one. This probability decreases while the number of iterations increases. This method converges in probability to the set of optimal solutions. Two parameters need to be regulated in this method: the initial temperature T_0 and the decreasing factor α. T_0 is chosen such as all the transitions are accepted at the beginning, as defined in Equation 6.3. α is chosen such as the final temperature T_α is close to zero, computed as presented in Equation 6.4, with $IterMax$ the maximum number of iterations (van Laarhoven and Aarts, 1987).

$$e^{-\frac{H(X')-H(X)}{T_0}} \approx 1, \forall (X, X') \tag{6.3}$$

$$\alpha = \sqrt[IterMax]{\frac{T_\alpha}{T_0}} \tag{6.4}$$

The simulated annealing was chosen to be compared to the stochastic descent, because previous studies have shown that simulated annealing may found better solutions than other meta-heuristic techniques in less computational time (Rabbani et al., 2014). The principle of the simulated annealing algorithm is presented in Algorithm 2 (Klement, 2014).

6.4.3 List algorithm

List scheduling algorithms are one-pass heuristics that are widely used to make schedules. Zhu and Wilhelm (2006) defined a standard list scheduling algorithm as the construction of a schedule by assigning each activity in the listed order to the first resource that becomes

Algorithm 2 Principle of the simulated annealing algorithm

Input: initial solution X, temperature T_0, decreasing factor α

$T = T_0$

while the stop criterion is not reached **do**

  Choose uniformly and randomly $X' \in V(X)$

  if $rand[0,1) \leq e^{-\frac{H(X')-H(X)}{T}}$ **then**

    $X = X'$

  Generate a new temperature $T = \alpha$ x T

idle. The list algorithm is used to build the solution X from the list Y, *i.e.* it assigns the tasks to the robots and the robots to the workstations over the planning horizon, according to the problem constraints. It is important to work with a list algorithm, because the meta-heuristic browses the set of lists Y. Thus the algorithm used needs to consider the order of the list to assign the tasks to the robots and the robots to the workstations over the planning horizon (Klement et al., 2017b). In short, from an initial randomly generated sequence of assembly, the list algorithm determines the minimum number of robots, the tasks' assignment and the allocation of the robots. Next, the meta-heuristic randomly permutes the jobs in the list. This new sequence runs in the list algorithm. This operating logic repeats until the stopping criterion (maximum number of iterations) is achieved. The list algorithm developed is outlined below in Algorithm 3.

6.4.4 Objective function

The objective is to find the solution X that minimises the number of robots required to achieve the cycle time desired. Algorithm 4 describes the whole method, with the example of simulated annealing as the meta-heuristic used (Klement, 2014).

6.5 Results

To test the proposed solution method, an instance consisting of 16 products to be assembled in the reconfigurable assembly line is generated. The product set is composed of a mix of 50% of product A and 50% of product B. Several initial sequences were generated considering this product mix. These sequences are the input to the hybrid optimisation approach. The stochastic descent and the simulated annealing were used to determine the sequence of products, the tasks assignment to the robots and the allocation of the mobile robots to the workstations. Both ran in approximately the same time. The literature dedicated to optimisation methods express an unanimous opinion over the good performances of the simulated annealing (Renzi et al., 2014). Thus, as expected, the search mechanism used by this meta-heuristic showed better performance and, consequently, a better sequence,

Algorithm 3 List algorithm

```
Input: list of products, list of tasks, processing times of each task
Output: sequence of jobs, assignment of tasks to robots, allocation of robots to workstations
for all products in the list do
    for all workstations do
        for the list of tasks do
            while there are tasks to be performed do
                if the task requires a robot then
                    if there are no robot in the workstation then
                        for all robots do
                            if the robot is available then
                                Call the robot to the workstation
                                Assign the task to the robot
                                Update robot's release time
                            else
                                Update the list of tasks to be performed
                    else
                        if the robot is available then
                            Assign the task to the robot
                            Update robot's release time
                        else
                            for all robots do
                                if the robot is available then
                                    Call the robot to the workstation
                                    Assign the task to the robot
                                    Update robot's release time
                                else
                                    Update the list of tasks to be performed
```

tasks' assignment and allocation of the robots to the workstations. In the remaining of this chapter, only results obtained using the simulated annealing are presented.

6.5.1 Sequencing of jobs and tasks assignment

The cycle time desired at each workstation is 30s, which correspond to the total processing time of common tasks. The first product is completed in 90s. After that, a product is released at every 30s. Therefore, the makespan desired for this set of 16 products is 540s. To determine the quantity of robots needed to achieve the makespan of 540s, the methodology proposed is run considering one robot available for the entire assembly line. If the makespan achieved is smaller than or equal to 540s, then stop. Otherwise, the number of robots available in the assembly line is incremented by one unit and the methodology is run again. This is repeated until the number of robots available is enough to achieve the makespan desired. The problem analysed is composed by a small-scale instance, thus this

Algorithm 4 Hybridisation of simulated annealing and a list algorithm.

Input: initial solution $Y \in \Omega$, temperature T_0, decreasing factor α, maximum number of iterations $IterMax$
$iter = 0$, $T = T_0$
$X = L(Y)$ ▷ a list algorithm is applied to the list Y
Solution record $RY = Y$, $RX = X$

```
while iter < IterMax do
    Choose uniformly and randomly Y' ∈ V(Y)
    X' = L(Y')
    if H(X') < RH then
        RY = Y'
        RX = X'
    else if H(X') ≥ H(X) then
        Y = Y'
        X = X'
    else
        Y = Y' and X = X' with the probability e^(-(H(X')-H(X))/T)
    iter = iter + 1
    Generate a new temperature T = α x T
```

number of iterations is enough to assure that the sequence given by the hybrid optimisation approach is, indeed, the best sequence. In Table 6.2, six sequences of products and the corresponding number of robots required to achieve the makespan desired are presented.

Table 6.2: Sequences of products and the number of robots required.

Sequence	Sequence of products	Number of robots
1	[A,B,A,A,B,B,A,B,B,A,B,B,B,A,A,A]	10
2	**[B,B,B,B,B,B,B,B,A,A,A,A,A,A,A,A]**	**5**
3	[A,A,A,A,A,A,A,A,B,B,B,B,B,B,B,B]	10
4	[B,B,B,B,A,A,A,A,B,B,B,B,A,A,A,A]	10
5	[B,B,A,A,B,B,A,A,B,B,A,A,B,B,A,A]	10
6	[B,A,B,A,B,A,B,A,B,A,B,A,B,A,B,A]	9

Sequence 1, that corresponds to the initial list Y, was generated randomly by the proposed algorithm. With this sequence, 10 robots are required to achieve the makespan desired. Sequence 2, that starts with the production of all products B followed by the production of all products A, is the best sequence given by the hybrid optimisation approach. It needs 5 robots to achieve the assembly cycle time desired, *i.e.* half of the number required by the initial sequence randomly generated. This best sequence shows that a lot size of 8 units must be chosen to minimise the number of robots needed to achieve the makespan of 540s. Sequence 3 keeps the lot size of 8 units, but changes the sequence in which the products are assembled: first all products A, then all products B. This sequence requests 10 robots to achieve the cycle time desired, *i.e.* twice of the robots required for the best solution. Thus, maintaining the lot sizes, but changing the assembly sequence leads to a worst solution. Therefore, the sequence of assembly has an impact on the number of mobile collaborative robots required to accomplish the makespan desired.

To evaluate the impact of the lot sizes on the number of robots required, three more sequences were generated: sequence 4, with a lot size of 4 units; sequence 5, with a lot size of 2 units; and sequence 6, with a lot size of 1 unit. Based on the best list given by the hybrid optimisation approach, all these sequences start with the assembly of products B, since this option seems to lead to better results. Sequences 4 and 5 require 10 robots and the sequence 6, 9 robots. These results show that the number of robots required depends on the sequence of assembly defined, not on the lot size chosen. In fact, as long as the sequence imposes a transition from a product A to a product B, the number of robots needed increases considerably, if compared to the best sequence, in which there is a single transition from product B to product A.

In the present case, it is advisable to assemble all products B and then all products A. To confirm these findings, two new sets were generated. Sequence 7, which is composed of 32 products: 16 products A plus 16 products B and sequence 8, which is composed of 64 products: 32 products A plus 32 products B. The results obtained for these instances are shown in Table 6.3. They confirm that the best solutions are obtained when transitions from A to B are avoided.

Table 6.3: Results given by the hybrid approach considering 32 and 64 products.

Sequence	Sequence of products	Number of robots
7	[BBBBBBBBBBBBBBBBAAAAAAAAAAAAAAAA]	5
8	[BBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBB AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA]	5

To further explore this issue, Figure 6.3 and 6.5 present Gantt charts, representing the tasks' assignment to the robots for sequences 2 and 3. Details of these charts, showing the transition from A to B and from B to A are presented in Figure 6.4 and 6.6, respectively. The triplet in the y axis represents the product, the workstation and the number of the task performed by the robot. Regardless the sequence, many gaps exist, indicating robots' idle times. They can be explained by the set of tasks' precedence constraints of products. Furthermore, only a single product is allowed at a workstation at a time. This may imply some waiting times for the robots, that have to wait the completion of common tasks before initiating the next specific task. In sequence 3, as observed in Figure 6.4, there is a repetitive standard in the assignment of the robots, that occurs due to the flow of assembly and the set of tasks' precedence constraints of products. During the transition from product A to product B, that happens from 245s to 300s, approximately, when the last task of product A (task_18) is completed, this pattern is interrupted. This discontinuity implies that 10 specific tasks can be performed in parallel: 7 tasks of product A and 3 tasks of product B. Thereby, to achieve the makespan desired, 10 robots are required. The same analogy is applied to the sequences 1, 4 and 5. Although in the sequence 6 there are as many transitions between the two types of products as in the other sequences, the pattern in the tasks' assignment is not broken. This explains why this sequence requires one less robot. In this case, there are 9 specific tasks, at maximum, to be performed in parallel. In sequence 2, on the other hand, as observed in Figure 6.6, the transition from product B to product A, that occurs from 245s to 290s, approximately, implies that only 5 specific tasks can be performed simultaneously: 2 tasks of product B and 3 tasks of product A. Thus, 5 robots are enough to achieve the makespan of 540s.

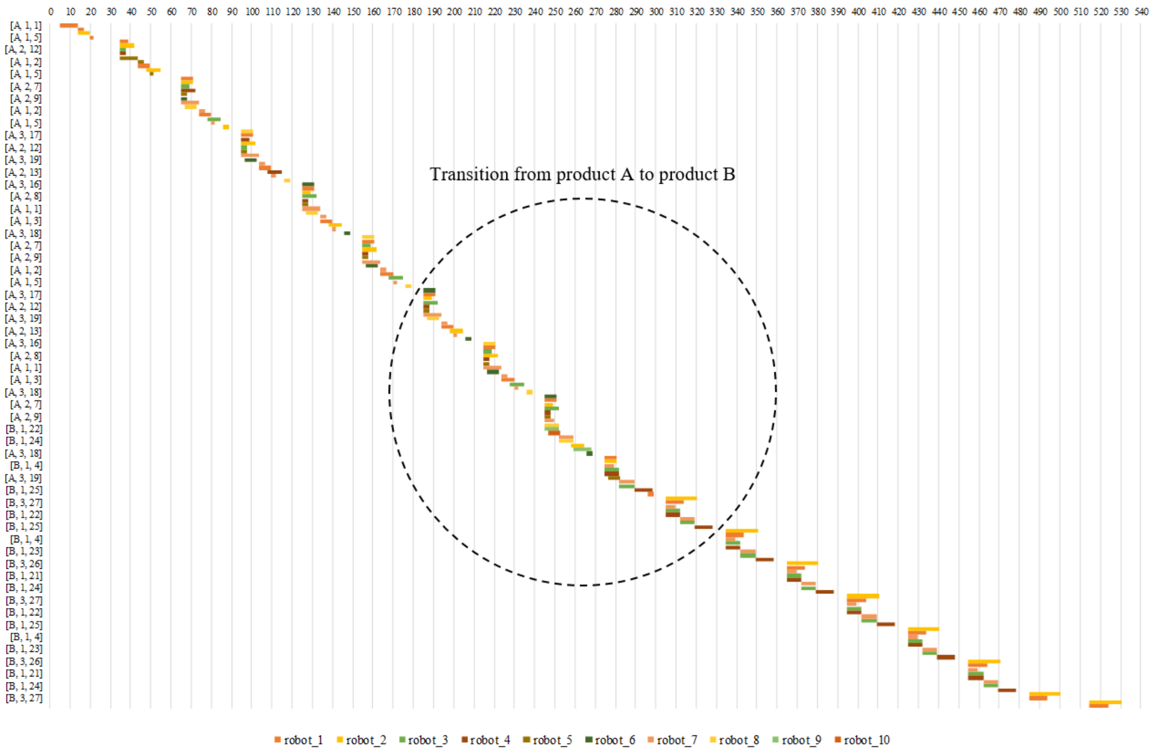


Figure 6.3: Tasks assignment of sequence 3.

During the transition from product A to product B (Figure 6.7), the greatest number of robots is required to achieve the cycle time desired. This occurs, because the assembly line has a product B at WS1 and a product A at WS2 and at WS3. This combination of products implies the execution of 15 specific tasks. This is the worst combination of products on the assembly line, the one that requires the greater number of specific tasks to be executed during a cycle time period.

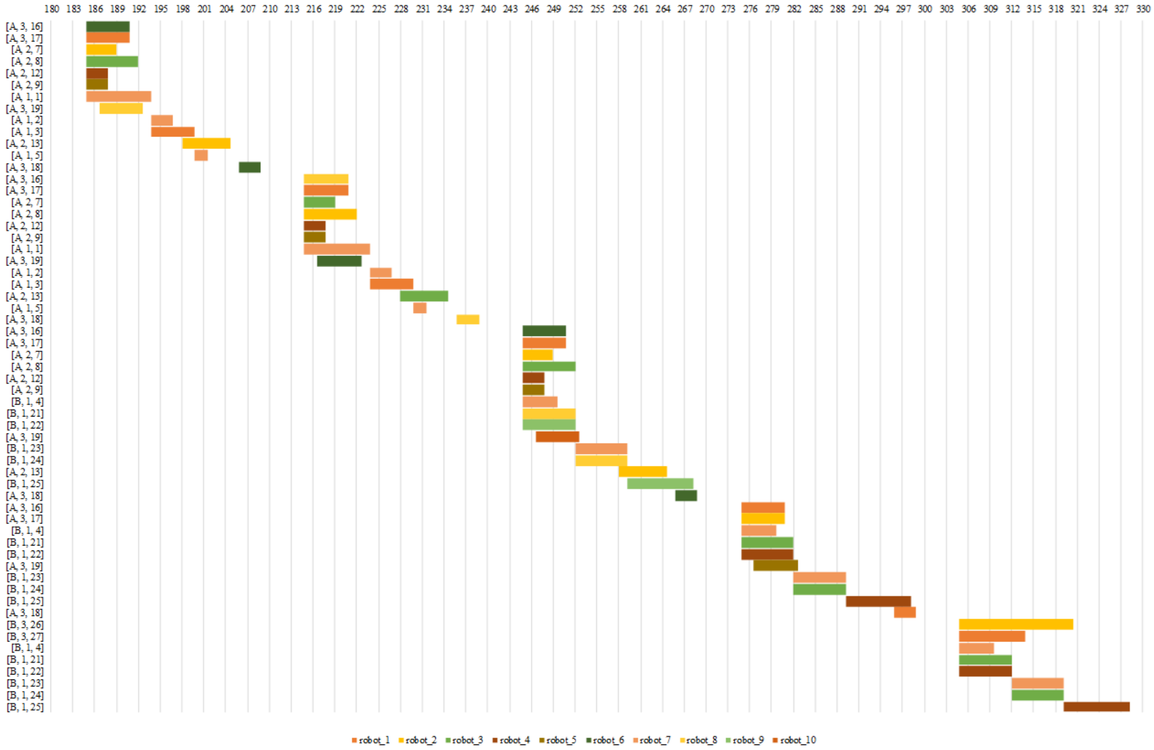


Figure 6.4: Tasks' assignment during the transition from product A to product B.

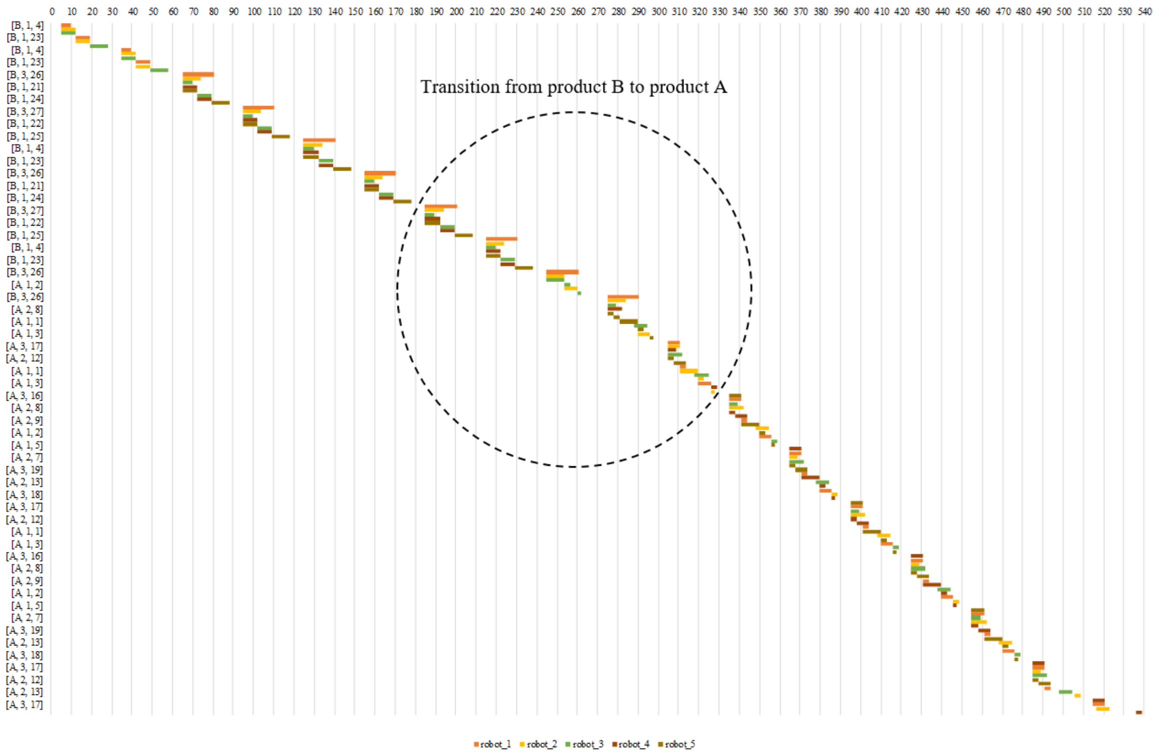


Figure 6.5: Tasks' assignment of sequence 2 (best sequence).

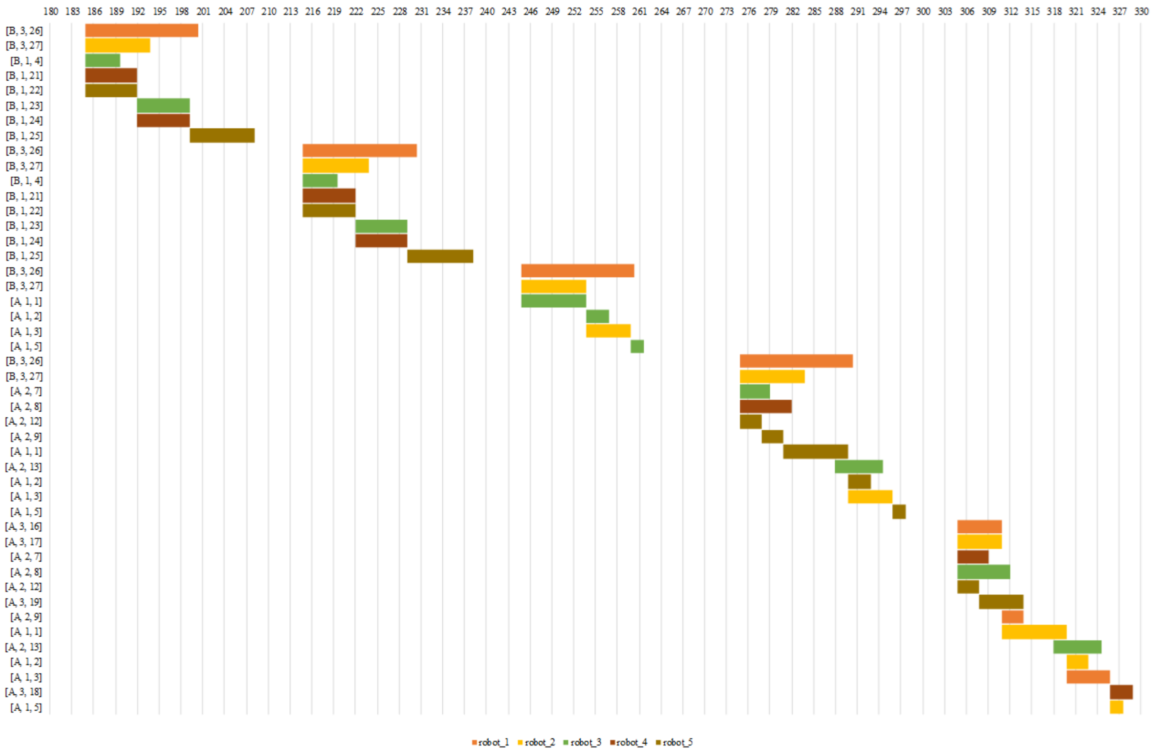


Figure 6.6: Tasks' assignment during the transition from product B to product A.

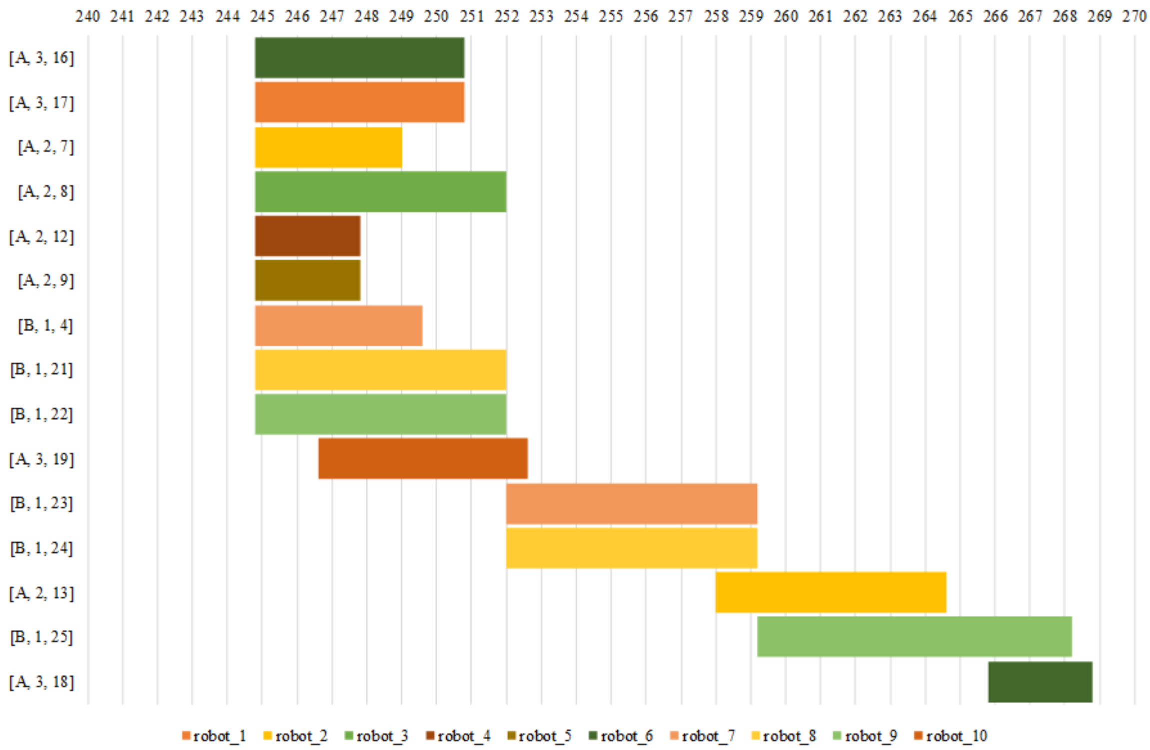


Figure 6.7: The worst combination, during the transition from product A to product B.

The results discussed so far indicate that the minimum number of robots required to achieve the makespan desired is imposed by the worst combination of products on the assembly line, which implicates the execution of the greater number of specific tasks. This conclusion has two consequences to the hybrid optimisation methodology developed.

The list algorithm allows the execution of a task if 1. the task is available to be performed, and 2. if there is an available robot in the system, either in the assembly line or at the buffer. In the case studied, the worst combination leads the list algorithm to call 10 robots from the buffer to the assembly line. For all the other combinations, the number of robots needed is lower than 10, which means that the robots are always available in the assembly line. Consequently, all the tasks start as soon as they are available. There are several tasks to be performed in parallel at the workstations. This incurs large idle time of robots and a large number of robots that must be at the same time at a given workstation. This situation might significantly difficult the use of mobile robots, if the assembly line has space restrictions for their allocation and displacement. These problems can be avoided if the list algorithm considers a time window to the execution of specific tasks instead of performing them as soon as they are available. In this case, a task has a time window with a lower limit (earliest start time) imposed by the completion of its precedence and an upper limit (latest start time) defined in order to allow all subsequent tasks to be completed before the cycle time desired. Then, the start time of a task is defined inside its time window, to minimise the number of robots in parallel at a given station. This implicates a greater time of certain robots in the buffer instead of in the assembly line. However, this time can be used for maintenance or battery charge operations, which were not considered in this study, but that are present in practice inevitably.

The proposed methodology is quite effective for small instances. In fact, for the example considered so far, the results were obtained in less than 12 minutes. Nevertheless, for real scale problems, with a larger number of products to be assembled and/or a larger number of workstations, the computational time may increase significantly.

Knowing that the minimum number of robots is imposed by the worst product combination can lead to a simplified approach to obtain a solution:

1. Generate all the possible combinations of products in the assembly line;

2. Determine the number of robots, for each combination, using the list algorithm proposed;

3. The minimum number of robots needed to achieve the cycle time desired is the one obtained for the combination found in step 2 that requires the greater number of robots; and

4. With the minimum number of robots, use the hybrid optimisation approach proposed to determine the best sequence and tasks' assignment.

Secondly, another implication of this analysis is that the worst product combination may imply a transition between two types of products. In such case, the methodology proposed tends to a solution where this transition is avoided, requiring large batches. In the example used, the best solution consists in assembling all products B, then all products A. This is against the lean method known as *heijunka*, where the production is levelled based on the average demand for each product in the portfolio, aiming at minimise inventories.

Average utilisation percentage of resources

This section discusses the average utilisation percentages of the resources for the best solution obtained (sequence 2, from Table 6.2). The average utilisation percentage of human resources is equal to 88.9%. However, since the tasks performed by humans are those that determine the cycle time of assembly at the workstation, it would be expected to be 100%. This does not occur due to the start-up and shut-down periods. For instance, when the assembly of the first product starts at WS1, the human resources are already available at WS2 and WS3. Yet, they can only perform their tasks after the product is released from WS1 and WS2, respectively. Thus, until the completion of the first product, the assembly line is passing through the start-up phase. The same analogy is applied to the shut-down phase, that initiate when the assembly of the last product, i.e. the sixteenth product, is completed at WS1.

A comparison among the makespan, the utilisation percentage of human resources and robots of the best sequence is shown in Figure 6.8.

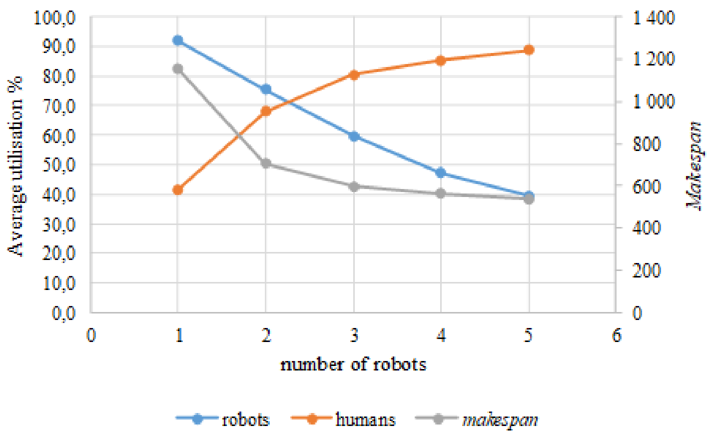


Figure 6.8: Average utilisation of human resources and robots of the best sequence.

With a single robot, the makespan is 1153.2s, which is larger than twice the value desired. This means that the assembly line cycle time cannot be achieved. The utilisation percentage of human resources is low, approximately 40%, while the utilisation of robots is high, superior to 90%. In this case, the assembly line cycle time is imposed by the robots. The human resources have a large idle time, because they need to wait for the completion of specific tasks, performed by the robots, before initiating their own tasks. Adding a second robot to the assembly line promotes a reduction of 39% of the makespan (from 1153.2s to 706.8s). The utilisation percentage of human resources increases to 68%, while the utilisation of robots decays to 75%. Nevertheless, even with two robots in the assembly line the makespan desired is not achieved. The addition of the third robot contributes to a reduction of 20% of the makespan (from 706.8s to 596.4s). The utilisation of human resources keeps increasing (from 68% to 81%) and the utilisation of robots keeps decaying (from 75% to 60%). Adding a fourth robot to the assembly line provides a reduction of 5% of the makespan, at the cost of a reduction on the utilisation of robots of 20%. The addition of the fifth robot, despite being necessary to achieve the makespan desired, contributes to a reduction of only 0.4% of the makespan. Therefore, the addition of up to 3 robots in the assembly line can be seen as an investment in production capacity that moves towards the achievement of the desired cycle time. On the other hand, adding additional capacity with four or five robots may represent an unjustified investment to reach the cycle time desired. This means that, from the third robot, the actual need to use more robots should be verified, because, as shown in Figure 6.9, the utilisation percentage of each of the five robots is low; the highest utilisation does not achieve even 50%. Thus, the trade-off between achieving the makespan desired and investing in mobile robots that might have low utilisation percentages should be considered. Other actions can be implemented to increase the efficiency of the assembly process in order to achieve the makespan, such as reducing the processing time of specific tasks or changing the type of tasks performed by robots.

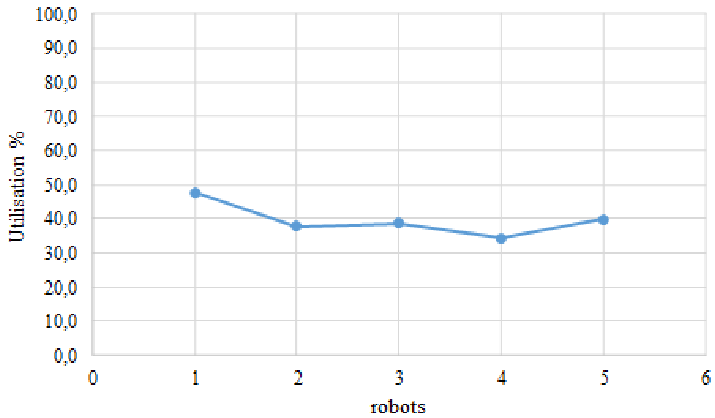
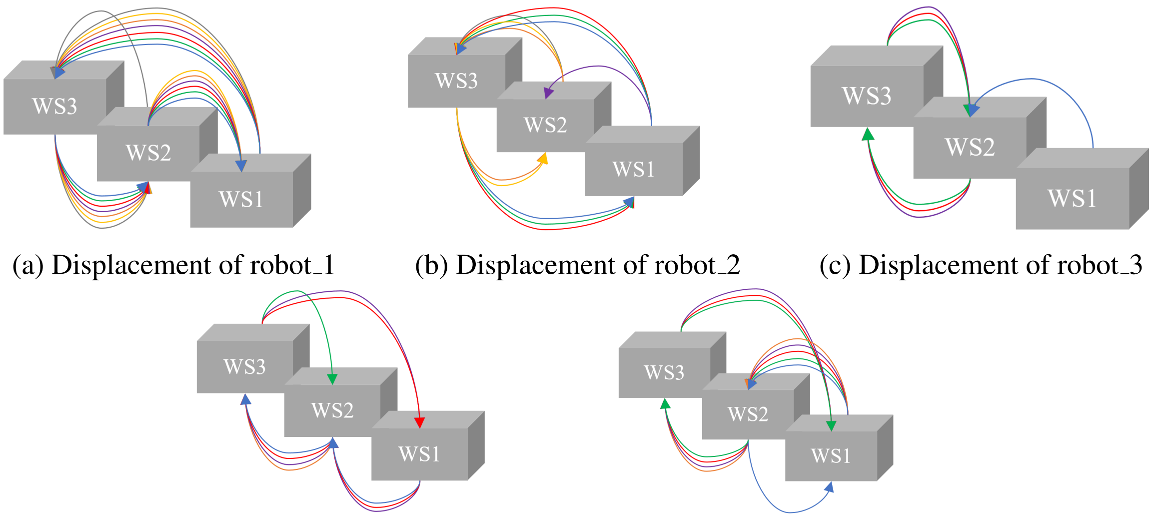


Figure 6.9: Utilisation percentage of each robot.

6.5.2 Allocation of robots at the workstations

The placement of the resources in the plant area is known to have a significant impact on manufacturing costs, work in process, lead times and productivity. A good placement of resources contributes to the overall efficiency of operations and can reduce until 50% the total operating expenses (Drira et al., 2007). In RMS, the resources should be arranged in a way that the reconfiguration process is facilitate, so that the manufacturing system can respond to sudden market changes (Cedeno-Campos et al., 2013). Multitasking collaborative mobile robots are an attractive form of workforce that can provide reconfigurability for assembly lines. They can dynamically change their work position to perform all the specific tasks of both different types of products and shift their capacity to where it is needed (Al-Zuheri et al., 2016). Furthermore, these robots characterise highly reconfigurable resources that can change their functionalities whenever necessary, to cope with changes in demand volume and product mix (Giordani et al., 2009). In pure manual assembly lines, human resources must be fully trained to complete the assembly of a whole product, which may be an expensive process. In contrast, there are many advantages of using multitasking mobile robots in assembly lines. Besides minimising cultural changes, the advantages include an easier line balancing, reduced buffer requirement, greater tolerance of work time variations and adjustability of the number of operators in response to the output requirement (Wang et al., 2007). They can also provide to the human resources an artificial force to perform hazardous activities reducing the ergonomic risk of strenuous tasks (Cohen et al., 2017).

In the problem studied, the mobile robots must be assigned to the workstations to perform the specific tasks, thus characterising a layout problem. The results given by the hybrid optimisation approach for the position occupied by each of the robots are presented in Figure 6.10 and Table 6.4. The robots are assigned to the specific tasks at fixed workstations and change their location according to the changes in tasks' local. Therefore, the arrows indicate the displacement of the robots. When a robot is required, the first action is to verify if there is a robot available at the workstation where the task should be performed. This allows to choose the closest robot and, consequently, to reduce its displacement in the assembly line. However, it does not guarantee that the displacement is the minimal.



(a) Displacement of robot_1 (b) Displacement of robot_2 (c) Displacement of robot_3

(d) Displacement of robot_4 (e) Displacement of robot_5

Figure 6.10: Displacement of the robots in the assembly line.

In Figure 6.10, the different colours of the arrows show a repetitive pattern of robots'

Table 6.4: Summary of displacements and number of specific tasks performed by the robots.

Robot_ID	Number of displacements	Workstation	Number of tasks performed	Total time (s)
Robot_1	21	1	10	60.0
		2	7	21
		3	16	172.8
Robot_2	11	1	9	54.6
		2	9	54.0
		3	13	93.0
Robot_3	11	1	19	118.2
		2	13	78.6
		3	3	9.0
Robot_4	11	1	18	114.0
		2	5	20.4
		3	9	48.0
Robot_5	11	1	24	152.4
		2	6	18.0
		3	7	42.0

displacement. For instance, robot_1 moves regularly from WS1 to WS3, from WS3 to WS2 and from WS2 to WS1, despite a single move from WS2 to WS3. More specifically, robot_1 starts the execution of specific tasks at WS1, then moves from WS1 to WS3, from WS3 to WS2 and from WS2 to WS1 (blue arrows in Figure 6.10a). Next, robot_1 moves from WS1 to WS3, from WS3 to WS2 and from WS2 to WS1 (green arrows in Figure 6.10a). After that, this pattern of displacement, *i.e.* WS1$\rightarrow$ WS3$\rightarrow$ WS2$\rightarrow$ WS1, is repeated four more times (represented by the red, purple, orange and yellow arrows). In the last cycle of displacement (grey arrows in Figure 10a), the robot_1 moves from WS1 to WS3, from WS3 to WS2, but, instead of moving from WS2 to WS1, it moves from WS2 to WS3. This last move represents the moment when robot_1 is called to perform a specific task of the sixteenth product, which is the last to be assembled in the line. Therefore, as there are no more products to be assembled in WS1, robot_1 moves to WS3 where its capacity is required, which explains the break in the pattern of displacement.

Moreover, the results show that all robots move among all workstations. Robot_1 is the first robot called to the assembly line. As long as it is available, it performs all the specific tasks that require a robot. The second robot is called to the assembly line only when a specific task needs to be performed, but robot_1 is occupied. This justifies the high number of displacements of the first robot. On the other hand, robot_3 makes the lowest number of displacements. This is because it performs many tasks at WS1, thus spending the most part of the time at this workstation. However, once it moves to WS2, it concentrates the execution of tasks between WS2 and WS3.

The tasks are relatively well distributed among the robots. Nevertheless, the robot_2 performs the lowest number of tasks, *i.e.* 31 tasks, but is the robot_4 that works during the lowest time, *i*.e. 182.4s. This means that robot_2 performs tasks with higher processing times. Both of these robots are called first to WS1, then move from WS1 to WS2 or WS3, from WS2 to WS3 and from WS3 to WS1 or WS2, thus showing the similar patterns of displacement.

Robot_5 works most part of time at WS1, such as robot_3 and robot_4. This may occur due to the high number of specific tasks that should be performed at this workstation: 4 tasks of product A and 6 tasks of product B. Thus, more robots are required at this workstation than at the others. However, this robot is ranked second in terms of number of displacements. It is called first at WS1, but then it moves from-to all the other workstations. This is because robot_5 is the last robot called to the assembly line. The robots called before are already established at some workstation. Thereby, when the list algorithm checks if there is an available robot at the workstation, it prioritises the choice of the robot that is already there. For this reason, robot_5 should move many times, in order to fulfil the capacity where it is needed.

The displacement time of robots among the workstations was ignored in order to simplify the problem. This choice led to the solutions presented in Figure 6.10, which shows a large number of robots' moves among different workstations. In practice, the displacement time cannot be ignored in assembly lines with a large number of workstations, thus, this variable should be incorporated in the list algorithm.

6.5.3 Fluctuations on product mix

The manufacturing industry is under tremendous pressure from buyers' market, ranging from fluctuations in demand volume to product mix (Wang et al., 2017). For this reason, the impact of these fluctuations in the reconfigurable assembly line should be studied. The same set of 16 products was considered. The mix of products was analysed ranging from 0% of product A and 100% of product B to 100% of product A and 0% of product B, in order to achieve the makespan of 540s. Both meta-heuristic techniques were applied, achieving the same best sequence. Following, the results are presented using the example of simulated annealing.

Regardless the product mix, 5 robots are sufficient to achieve the makespan desired. As outlined in Table 6.5, a pattern emerged in terms of the best sequence of assembly: it is better to assembly all products B and then all products A. This behaviour has been explained in section 6.5.1.

The number of specific tasks of product A is greater than the number of specific tasks of product B. Thereby, the more products A in the mix, the more specific tasks to perform. Nevertheless, despite the successive increment in the number of products A, the same 5 robots are required and the makespan remains 540s. This means that the 5 robots can

Table 6.5: The best sequence of assembly given by the hybrid optimisation approach.

Product mix	Best sequence	Average utilisation % of robots
0%A - 100%B	[BBBBBBBBBBBBBBBB]	40.9
10%A - 90%B	[BBBBBBBBBBBBBBAA]	40.1
20%A - 80%B	[BBBBBBBBBBBBAAAA]	39.9
30%A - 70%B	[BBBBBBBBBBBAAAAA]	39.8
40%A - 60%B	[BBBBBBBBBAAAAAAA]	39.6
50%A - 50%B	[BBBBBBBBAAAAAAAA]	39.5
60%A - 40%B	[BBBBBBBAAAAAAAAA]	39.4
70%A - 30%B	[BBBBBAAAAAAAAAAA]	39.3
80%A - 20%B	[BBBBAAAAAAAAAAAA]	39.2
90%A - 10%B	[BBAAAAAAAAAAAAAA]	39.0
100%A - 0%B	[AAAAAAAAAAAAAAAA]	38.8

perform more specific tasks in the same time. This can happen depending on the tasks' assignment to the robots, i.e. for each product mix, the distribution of tasks among the robots is different, so that they can perform a greater number of specific tasks in the same time. For example, in the product mix of 10 of A and 90% of B, the robot_2 is the least used. In the mix of 20% of A and 80 of B, the tasks are redistributed among the robots, in a way that the utilisation of the robot_2 increases. However, the utilisation of the others decreases. In the mix of 50% of A and 50% of B, the utilisation of robot_3 and robot_4 increases and of the others decrease.

While the number of specific tasks increases as the percentage of products A increases, the average utilisation of robots decays. Product B does not have specific tasks at the WS2. Thus, when the product mix is composed of 100% of product B, the standard of the tasks' assignment and displacement of robots varies between WS1 and WS3. This implies that a small set of tasks' precedence constraints must be respected. Indeed, only the precedence of specific tasks of WS3 must be attended. The robots do not have to wait for the completion of many specific tasks, therefore they are occupied the most part of the time, which provides higher utilisation rates. In contrast, when the product mix if composed of 100% of products A, the set of tasks' precedence constraints is large, thus the robots have higher idle times. Thereby, different product mixes imply different sets of tasks' precedence constraints that may affect the utilisation percentage of robots. In addition to that, when the product mix varies from 10% of product A and 90 of product B to 90% of product A and 10% of product B, the transition between the types of products impacts on the utilisation of robots when the pattern in the tasks' assignment is interrupted.

6.5.4 Fluctuations on demand volume

In assembly lines, changes in demand volume can be accommodated by adjusting the cycle time of the products. For instance, when the demand volume increases, it means that the products have to be assembled in less time, thus requiring a reduction of the cycle time. In the assembly line studied, the cycle time is 30s, imposed by the common tasks, performed by human resources. Thus, increments and decreases in the cycle time were considered, for the same set of 16 products, in order to analyse the impact of fluctuations on demand volume. The results are presented in Table 6.6, using the values given by the simulated annealing. They show the range in which the same 5 robots are sufficient to achieve the makespan desired.

Table 6.6: The impact of variations of the cycle time on the makespan and the number of robots.

Cycle time (s)	makespan (s)	Number of robots	Average utilisation %	
			of humans	of robots
38	684	4	73.3	39.4
37	666	5	74.9	32.3
36	648	5	76.5	33.2
35	630	5	78.3	34.1
34	612	5	80.2	35.1
33	594	5	82.2	36.1
32	576	5	84.3	37.2
31	558	5	86.5	38.3
30	540	5	88.9	39.6

The increment in the cycle time indicates a decrease in the demand volume. In other words, increasing the cycle time implies increasing humans' and robots' idle times. Thus, at some point, less robots will be needed. In this particular case, the assembly line studied can cope with increments in the cycle time up to 23% (37s), using the same 5 robots. Increments greater than 23% leads to the need of one less robot. This might also lead to a reduction of the number of workstations by redistributing tasks among human resources. However, this was not tested in this study.

The decrease in the cycle time, on the other hand, indicates an increment in the demand volume. The line balancing of the assembly line studied was done considering a cycle time of 30s. Therefore, it cannot accommodate decreases in the cycle time without considering the addition of a new workstation. Assuming that this is not a limitation and that the cycle time can be reduced and accommodated by the same number of human resources, an increment in the demand volume may lead to a situation in which the cycle time is no longer determined by the common tasks, but by the specific tasks. Considering the best sequence of assembly for the set of 16 products, *i.e.* the assemble of all products B and then all products A, if the cycle time is reduced to 29s, it is still imposed by human resources; but if it is reduced to 28s, it becomes to be imposed by the robots. From this moment on, it means that the existing number of robots is not enough to achieve the makespan desired.

At each workstation, the set of tasks' precedence constraints of products must be respected, thus establishing the critical path. For product A, the critical path at WS1 is 16.8s, given by the sequence of task_1, task_3 and task_5; at WS2 is 27.6s, given by the sequence task_102a, task_12 and task_13; and at WS3 is 28.8s, given by the sequence task_104a, task_104b and task_18. For product B, the critical path at WS1 is 23.4s, given by the sequence task_21/task_22, task_23/task_24 and task_25; at WS2 and WS3, the critical path is given by the common tasks, thus depending on the cycle time considered. Taking this into account, the highest time of the critical paths determines the lower boundary to which the cycle time can be reduced, using the same number of robots to achieve the makespan desired. Therefore, the assembly line can cope with a reduction of only 4% (28.8s) in the cycle time, using the same 5 robots. Reductions greater than 4% may require more workstations. In turn, adding new workstations to the assembly line implicates a new line balancing, by redistributing tasks among human resources.

The average utilisation percentage of human resources and robots are also shown in Table 6.6. They behave as expected. The utilisation percentages of both decreases with the increment of the cycle time (from 30s to 37s). This occurs because increasing the cycle time means increasing the idle time of robots and human resources, as discussed above. When the cycle time is 38s, the utilisation percentage of human resources decreases, but the utilisation of robots increases. This situation requires one less robot to achieve the makespan, thus the utilisation of robots increases.

6.6 Discussion

The findings suggest that the collaboration of human resources and mobile robots in assembly lines can promote benefits. Attributing common tasks to humans and specific tasks to robots facilitates the training of human resources, which have to perform the same tasks, regardless the type of product. This contributes to the reduction of errors, thus to the improvement of the products' quality. However, this division of tasks is done a priori, which may lead to a situation in which the increment of robots in the assembly line provides very little gain in terms of makespan, at the cost of high decays in their utilisation percentage. This may represent a high investment in additional mobile robots with a doubtful return. Therefore, at some point, the addition of new robots must be rethought and replaced by other actions, such as the revision or the optimisation of the tasks to be performed. Other possibility is to address the problem in such a way that the line balancing is done considering common and specific tasks simultaneously. The decision, in this case, should be which task (common or specific) should be performed at each workstation, by whom (human resources or robots), in order to minimise the number of robots required. Nevertheless, the advantages of the aforementioned division of tasks a priori are lost.

Regarding the sequencing problem, for the considered instances, the optimal solution always tends to the same result: assemble all the products B and then all products A, thus leading to large lot sizes. As discussed in section 6.5.1, this happens because the transition between a product A and B lead to what was called the worst combination, which implies the execution of the larger number of tasks during a cycle time period. In this case, the worst combination is represented by a product B at WS1 and a product A at WS2 and WS3. These observations can lead to three main conclusions:

- The minimum number of robots required to achieve the makespan desired is given by the worst combination. The other combinations might require a lower number of robots, but, since the robots are available in the assembly line, they are called to perform the specific tasks as soon as they are available. This implicates large idle times of robots and the presence of a large number of robots in a given workstation simultaneously. To avoid this situation, the list algorithm proposed must be improved in order to choose the start time of a given task, considering a time window, with the objective to minimise the number of robots. This may provide solutions that request a lower number of robots at the workstations simultaneously, facilitating the introduction of mobile collaborative robots in assembly lines with space restrictions. On the other way, this may free more robots to the buffer during certain periods, facilitating the battery charge and maintenance activities.

- The proposed methodology might be improved. In fact, knowing in advance which is the worst combination might reduce the search space, speeding up the achievement of the best solution, which will be essential in real size assembly problems.

- The distribution of specific tasks among workstations must be done to guarantee that the worst combination will not correspond to a transition between two products. As it has been discussed, if this occurs, the solution tends to avoid this transition, leading to large batch sizes, which is against the lean principle of *heijunka*. Once again, this might mean that the a priori division of tasks amongst human resources and robots can provide sub-optimal solutions.

In respect of the tasks' assignment and allocation to the workstations, there is a repetitive behaviour of the robots. This impacts positively in their introduction and use in reconfigurable assembly lines, because each robot can be programmed to perform the same set of tasks and displacement among workstations. In lean, the sequence of assembly is defined by the demand, following the *heijunka* principle, to assure the line balancing and to cope with fluctuations on demand volume. In the described case study, the mobile collaborative robots can contribute to this both issues; shifting their capacity to where it is required and using the same number of robots to cope with different cycle times, respectively.

As discussed, adding as many robots as necessary to achieve the makespan desired may represent very slightly improvement of the makespan at the cost of low utilisations of robots. Thus, this may represent a substantial investment to improve the reconfigurability of the assembly system, but in which these highly adjustable resources might have underused capacity. To avoid this problem, the assignment of tasks to the robots should not be performed without an attempt to improve specific tasks. In other words, robots should be added to the assembly line as long as they represent a significant reduction of the makespan. If the reduction is not sufficient to achieve the desired cycle time, instead of adding more robots it is advisable to optimise the execution of specific tasks.

Additionally, the utilisation percentages, presented in section 6.5.1, show that, in this case studied, human resources have a utilisation near to 100%, performing repetitive tasks, while the utilisation of robots are below 50%. This is against what is promoted by Industry 4.0 paradigm that seeks a more human friendly working environment. Thus, the division tasks between humans and robots must be rethinked. This, once again, indicates that assembly line balancing strategies should consider the division of tasks between robots and human resources simultaneously.

The introduction of collaborative robotics indeed contributes to the improvement of the reconfigurability of assembly systems. RAS are designed for rapid changes in structure, in terms of capacity and functionality, within a product family (Bortolini et al., 2017; Yu et al., 2003). Therefore, *customisation,* particularly, customised flexibility, is an intrinsic characteristic of this type of system. The multitasking collaborative mobile robots are highly adjustable resources that can be added to or removed of assembly lines seamless. They allow for the gain of *modularity* in such that they characterise autonomous compatible functional units, *i.e.* modules, that can be plug-and-play to the workstations, are capable of performing a large number of different tasks and interact with one another in real time (Zheng et al., 2018). Plug-and-play environments are made of standard data communication protocols amongst resources, enhancing the data acquisition capabilities of devices and applications (Koren et al., 1999). This can reduce the costs of data integration and communication, therefore increasing the *integrability* of assembly systems. In addition to that, the multitasking mobile robots improve the means of reconfiguration by allowing the change of robots' functions and the complement of workstations' capacity for particular needs, impacting directly on the adaptability of the assembly system.

Diagnosability, in turn, seems to not be implemented in the assembly line studied. This may be the reason why the transition between the two types of product does not occurs smoothly, affecting the tasks' assignment and the number of robots required to achieve the makespan desired. Nevertheless, this characteristic can be implemented in RAS with the help of other Industry 4.0 technologies rather than collaborative robotics, such as reconfigurable inspection machines (RIM) and 3D scanning for automated quality inspection. These novel technologies may contribute to real time processing, thus enabling diagnosability (Maganha et al., 2018). Therefore, the introduction of collaborative robotics in assembly lines may not leverage the diagnosability of the system, but the presence of this characteristic may impact on the tasks' assignment and the number of robots needed, since it can provide more efficient transitions between different types of products. This indicates that not only the enabling technologies of Industry 4.0 may leverage the reconfigurability in manufacturing systems, but that this is a two-way relationship, in which the implementation of the core characteristics of reconfigurability can soften the impacts of the introduction of Industry 4.0 technologies.

6.7 Conclusions

This chapter analysed the potential of collaborative robotic technologies in leveraging the reconfigurability of manufacturing systems and proposed a model-based approach to study the impact of the introduction of this technology in assembly lines. In addition, it characterised some relevant lot sizing and sequencing decisions that may affect the performance of assembly lines.

In short, the introduction of collaborative robotics can leverage the reconfigurability of assembly lines through the improvement of its core characteristics. Customisation is an intrinsic characteristic of RAS. Particularly, in the assembly line studied, the collaborative mobile robots contribute to the leverage of modularity, integrability and adaptability. Although diagnosability could not be embedded by collaborative robotics in this case, other Industry 4.0 technologies might enable the implementation of this characteristic in assembly lines. Therefore, this is a two-way relationship: Industry 4.0 technologies can leverage the reconfigurability of RMS, as well as the reconfigurability, *i.e.* its core characteristics, can soften the impacts of the introduction of these novel technologies.

However, some drawbacks of using mobile collaborative robots were discussed along this chapter. Further research is required to solve them, leading to solutions where the use of mobile collaborative robots improve assembly lines reconfigurability without excessive investments and without putting in cause some lean manufacturing principles, such as *heijunka*, that have already proven to be effective in assembly lines.

The proposed approach was tested using a small-scale instance, showing its ability to solve real-world problems. Two meta-heuristics were used: stochastic descent and simulated annealing. Both achieved good results in relatively small computational times. Future research should consider large-scale instance and further constraints, such as considering displacement time for robots in the assembly line, and setup times when the robot change from one task to another, to obtain a more realistic approach of the problem. Moreover, the integration of robots assistance in manufacturing is a relevant research concern (Giordani et al., 2009). Evaluating these and other aspects of the Industry 4.0 paradigm will allow the design and operation of quite efficient reconfigurable assembly lines.

Part V Conclusion

Contents

Chapter 7 Conclusion

The research presented in this thesis considered multiple objectives, all of them aiming to get a better understanding about RMS. The MMA was used to achieve the research goals. The contributions of this thesis move towards theory and practice. The QE part provided new theoretical concepts, that contributed to the progress of the scientific literature in terms of which actually are the core characteristics of reconfigurability, how they impact on the operational performance of manufacturing systems and their influence on different business production strategies. The results obtained with the QE may also allow manufacturing companies to assess the current level of reconfigurability implemented and guide them through the identification of the actual need of reconfigurability. The literature review highlighted many key areas that may direct future research. The CS provided evidences that the reconfigurability can be implemented in practice, and can be leveraged with the aid of Industry 4.0 technologies, such as mobile collaborative robotics.

7.1 Summary of results

In the following, the main contributions of each chapter are summarised.

Part II: Quantitative empirical approach

The core characteristics and the implementation level of reconfigurability (Chapter 2). A questionnaire survey was developed and applied to manufacturing companies to identify which are indeed the core characteristics of reconfigurability and measure the extent to which they are implemented. The results support the existence of five core characteristics of reconfigurability instead of the six predicted in the literature. Convertibility and scalability merge and are understood as one unique dimension, because both are directly related to manufacturing systems responsiveness to abrupt changes and future market conditions, and both must be considered at the design stage of reconfigurable systems. In short, reconfigurability has five core characteristics: customisation, modularity, integrability, diagnosability and adaptability (convertibility plus scalability). In general, manufacturing companies present average levels of reconfigurability implemented. Customisation and adaptability, which have been considered critical reconfiguration characteristics, have a higher level of implementation than diagnosability, integrability and modularity, which enable a rapid reconfiguration, but do not guarantee modifications in production capacity and functionality. Thus, the findings show that while current production systems seem to be prepared to be reconfigurable, they lack the characteristics that allow for a rapid reconfiguration. The findings also suggest that the novel technologies promoted by the Industry 4.0 paradigm, such as big data analysis and real time collection, flexible transportation systems and mobile collaborative robotics, might significantly contribute to the increase of manufacturing systems' reconfigurability.

Impacts of reconfigurability on the operational performance of manufacturing systems (Chapter 3). The objective of this chapter was to analyse the core characteristics of reconfigurability and its impact on manufacturing systems' operational performance empirically. Four performance indicators were measured: quality, delivery, flexibility and cost. The findings support the idea that the core characteristics actually impact on the operational performance of manufacturing systems. Customisation guides the system for customers' needs, contributing to the improvement of fast delivery. Diagnosability is the core characteristic that supports the quality performance of the manufacturing system. Adaptability might improve systems' operational performance in terms of flexibility, but it might provide greater performance if integrability and modularity are also implemented. Modularity and integrability enhance operational performance of manufacturing systems in terms of delivery and flexibility. However, the impact on operational performance is not only a matter of which of the core characteristics are implemented, but also of the production environment, in terms of variability to which they are subjected, the type and the complexity of products and routings; the responsiveness required and the dependency that exists among the characteristics.

Analysis of reconfigurability in different business production strategies (Chapter 4). This chapter contributes by analysing the implementation of reconfigurability in companies using different business production strategies, namely make-to-order, engineer-to-order, assembly-to-order and make-to-stock. The results suggest that the core characteristics can contribute in different ways, because each production strategy has specific requirements, such as variability in demand volume and product mix, that influence the need of reconfigurability of the manufacturing system.

Part III: Systematic literature network analysis

Literature review on the layout design of RMS (Chapter 5). A comprehensive systematic literature review has been conducted, considering key issues that have influenced the research on the layout design of RMS. Different quantitative bibliometric analyses have been carried out, namely main path and cluster analysis. The findings show that the layout design of RMS has evolved substantially in complexity. In fact, the layout design of conventional manufacturing systems no longer supports the layout design of RMS, in which new characteristics, such as reconfigurability, should be considered. Four clusters were identified, pointing a trend towards the investigation of four perspectives: RMS design methodologies, RMS core characteristics for configuration selection, layout design and solution approaches. This suggests that the layout design of RMS cannot be seen in isolation. Each of these perspectives presents critical areas and emerging topics that are underrepresented and require further investigation.

Part IV: Case study

The use of mobile collaborative robotics to increase the reconfigurability of assembly lines (Chapter 6). The main contribution of this chapter relies on the identification of the advantages and drawbacks of introducing mobile collaborative robots on assembly lines. The advantages include facilitating the training of humans and the reduction of errors. However, adding as many robots as required to achieve the cycle time desired may represent a significant investment that slightly improve the performance of the system. Therefore, to avoid this, before adding robots to the assembly lines, other actions, such as optimising the execution of tasks, must be considered. Furthermore, the a priori division of tasks between humans and robots can lead to solutions requiring a large number of robots, with low utilisation percentages, to achieve the cycle time desired. Thus, it is suggested that layout configuration problem, tasks assignment to human and robots, products scheduling and line balancing problem must be considered in an integrated way to achieve the desired cycle time and flexibility, with the minimum number of robots. Despite these drawbacks, it can be concluded that, if implemented correctly, mobile collaborative robots can improve the reconfigurability of assembly lines to cope with varying volume demand and product mix.

7.2 Future research

Future research directions are suggested to be pursued, as follows:

Replicate the questionnaire survey. The data for the survey were collected from firms based in Portugal. The replication of this questionnaire in other countries is recommended for future research in order to confirm its findings. The questionnaire proposed could also be the basis for the development of an index to measure reconfigurability, using multicriteria decision techniques.

Investigate the four perspectives identified on the literature review. Several critical areas were identified in the four perspectives highlighted in the literature review on the layout design of RMS. However, only a few were addressed in this thesis. Future research should focus on the remaining topics that include, but are not limited to: adapting design methods of conventional manufacturing systems or creating new ones to deal with the layout design of RMS; investigating how the core characteristics of reconfigurability behave in relation to each other; identify what triggers the need for the re-layout of an existing manufacturing system; exploiting the use of simulation-optimisation to cope with the uncertainties of the layout design.

Analyse the impacts of the introduction of other technologies promoted by the Industry 4.0 paradigm. The integration of reconfigurability and Industry 4.0 technologies is a relevant concern. Thus, the relationship between reconfigurability and other technologies rather than mobile collaborative robotics should be analysed. This might provide tentative evidence of how they can be transferred and implemented in actual systems.

Improve the constructive heuristic. Future research should consider a time window instead of assigning tasks to the mobile robots as soon as they are available to be performed. This can provide solutions that may require a lower number of robots to achieve the cycle time desired. Other constraints, such as the displacement time of robots, that cannot be ignored in practice, as well as setup times when the robot changes from one task to another, should also be considered in the problem formulation to obtain a more realistic approach.

Cope with the drawbacks of introducing mobile collaborative robots on assembly lines. Further research is required to solve the inconveniences of the introduction of mobile collaborative robotics on assembly lines. These studies should lead to solutions in which the use of mobile collaborative robots leverage the reconfigurability without excessive investments and without putting in cause lean manufacturing principles, such as *heijunka*, that have already proven being effective in assembly lines.

Part VI Appendix

Contents

Appendix A Manufacturing strategies and layout design practices

General instructions

This questionnaire is part of a PhD research in Mechanical Engineering of University of Coimbra, conducted by the researcher Isabela Maganha, under the guidance of Professor Cristóvão Silva.
This study aims to identify and to explore the main manufacturing/assembly strategies, the production system characteristics, the layout design practices and the performance of your company.
This questionnaire is composed by 13 questions, most of which uses a 7 points scale (1 = strongly disagree and 7 = strongly agree). The estimated time to answer these questions is 10 minutes.
Read each item carefully to assign the most appropriated response for the current situation of your company. The questions refer to its production processes, equipment and layout configuration. When answering, refer always to the dominant activity, the average performance and the main competitor(s) of your company.
The questionnaire is anonymous and all responses will be treated confidentially.
The questions should be answered by the Production Manager (or equivalent).

Before beginning, please provide the following information:

Company's name:
Country:
Year of foundation:
Number of employees:
Your job title:
Select the industry type that best describes your company's activities:

Section A

From now on, please always refer to the dominant activity, *i.e.* which best represents your plant.

How would you describe the complexity of the dominant activity?

Modular product design [1]	1	2	3	4	5	6	7	Integrated product design [2]
Very few parts/materials, one-line bill of material	1	2	3	4	5	6	7	Many parts/materials, complex bill of material
Very few steps/operations required	1	2	3	4	5	6	7	Many steps/operations required

[1] The modular design describes a product made up of standardised and independent components that can be combined in various ways to create different products.

[2] The integrated design describes a product composed of connected and dependent components, which must be adjusted to change the functionality of this product.

To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
Your demand fluctuates drastically from week to week	1	2	3	4	5	6	7
Your total manufacturing volume fluctuates drastically from week to week	1	2	3	4	5	6	7
The mix of products you produce changes considerably from week to week	1	2	3	4	5	6	7
Your supply requirements (volume and mix) vary drastically from week to week	1	2	3	4	5	6	7
Your products are characterised by a lot of technical modifications	1	2	3	4	5	6	7
Your suppliers frequently need to carry out modifications to the parts/components they deliver to your plant	1	2	3	4	5	6	7

Select the statement that best fits your production system.

The products are dispatched immediately after receiving the customer's order
The assembly operations only take place after receiving the customer's order
The manufacturing operations only start after receiving the customer's order
Your products are designed and manufactured after receiving the customer's order

To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
We can say that our layout configuration changes several times a year	1	2	3	4	5	6	7

How important do you consider the following criteria when you change the layout configuration of your production system?

	Not at all important	Not very important	Somewhat important	Neither important or unimportant	Somewhat important	Very important	Extremely important
Work in progress	1	2	3	4	5	6	7
Lead time	1	2	3	4	5	6	7
Throughput	1	2	3	4	5	6	7
Material handling costs	1	2	3	4	5	6	7

How is the layout configuration of your dominant activity characterised?

Process layout
Product layout
Cellular layout

Section B

Remember to answer considering the plant's dominant activity.

To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
The major equipment of our manufacturing system can be easily added to, or removed from, the shop floor	1	2	3	4	5	6	7
Our equipment is made of several functional modules that can be easily added/removed	1	2	3	4	5	6	7
The major equipment of our manufacturing system can be easily reorganised to obtain an adapted configuration to manufacture new products	1	2	3	4	5	6	7
Our material handling system (between work-stations) allows an easy rearrangement of the process flow, by adding/ignoring operations, according to the product to be manufactured [3]	1	2	3	4	5	6	7
Our manufacturing system is composed by hardware and software modules that can be integrated quickly and reliably [3]	1	2	3	4	5	6	7

[3]Items discarded after the EFA, because the loaded factor not exceeded the generally recommended minimum value of 0,4.

To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
We can integrate equipment rapidly and precisely by a set of mechanical, informational and control interfaces in our production system	1	2	3	4	5	6	7
Our equipment is operated/coordinated by an integrated control system exploited in an open-architecture environment	1	2	3	4	5	6	7
Our manufacturing system allows an easy integration of new equipment and new technologies	1	2	3	4	5	6	7
Our equipment and our control system were designed with interfaces that facilitate the integration of new components	1	2	3	4	5	6	7

To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
The location of our equipment on the shop floor was chosen considering the need to produce an entire product family	1	2	3	4	5	6	7
Our manufacturing system's capacity and flexibility (hardware and control system) were designed to match the production needs of a product family	1	2	3	4	5	6	7
Our control system, supported by an open-architecture technology, can be customised to have the exact control functions needed	1	2	3	4	5	6	7

To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
The capacities of our manufacturing system and of our equipment can be easily transformed to respond to changes in production requirements [4]	1	2	3	4	5	6	7
We can easily stop equipment operation and reconfigure its functions to manufacture a new product type	1	2	3	4	5	6	7
We can change quickly from manufacturing/assembling one product to another, if they are from the same family	1	2	3	4	5	6	7
Our manufacturing system allows an easy switch between existing products and can adapt to new/future products	1	2	3	4	5	6	7

To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
Our production capacity can be changed by adding/removing equipment or by changing the system's components [3]	1	2	3	4	5	6	7
Our manufacturing system can easily respond to unexpected equipment failures	1	2	3	4	5	6	7
We can easily add equipment, at any stage of the production process, without interrupting operations for long periods	1	2	3	4	5	6	7
Our throughput can be changed, in a relatively short time, to respond to demand changes	1	2	3	4	5	6	7

[4] Items discarded after the standard CFA refinement procedures.

[3] Items discarded after the EFA, because the loaded factor not exceeded the generally recommended minimum value of 0,4.

To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
Our manufacturing system can automatically detect defective products, diagnose their root causes and reset its parameters to restore the initial situation	1	2	3	4	5	6	7
Our manufacturing system includes inspection resources that allow the detection of quality defects in real time	1	2	3	4	5	6	7
Our manufacturing system uses inspection equipment that can be easily reconfigured for use in different stages of the production process	1	2	3	4	5	6	7
In a start-up phase, we can adjust the manufacturing system's parameters, thus reducing the ramp-up time, because we have mechanisms for the quick diagnosis of problems with quality	1	2	3	4	5	6	7
Our manufacturing system can automatically identify the source/cause of failures or problems with quality	1	2	3	4	5	6	7

Section C

From now on, consider your production system average performance and the group of competitors that are direct benchmark for your plant.

How does your current performance compare with that of your main competitor(s)?

	Low end of industry	Lower than	Somewhat lower than	Equivalent	Average	Better than	Superior
Conformance to product specification	1	2	3	4	5	6	7
On time delivery	1	2	3	4	5	6	7
Fast delivery	1	2	3	4	5	6	7
Flexibility to volume change	1	2	3	4	5	6	7
Flexibility to product mix change	1	2	3	4	5	6	7
Unit cost of manufacturing	1	2	3	4	5	6	7

Appendix B A theoretical background for the reconfigurable layout problem

Presented at the 27^{th} *International Conference on Flexible Automation and Intelligent Manufacturing* (FAIM2017). Published in *Procedia Manufacturing*.

Abstract

The production system configuration must be able to adapt to varying market demands. The global competition, high product variety and variable volumes require the launch of products with short life cycle and high customisation degree. Thus, the approaches to solve this problem should achieve more flexible layouts, while optimising performance measures. This work presents a systematic literature review of the RLP, which has shown potential to satisfy the current manufacturing needs. Specifically, it combines a bibliometric, a network and a content analysis to verify the existence of clusters and the evolution of this subject over the years.

B.1 Introduction

In today's manufacturing environment, flexibility is one of the most important parameters to facility layout design, which is essential for market survival (Raman et al., 2009). The flexibility provides the capacity needed to produce several products in the same system and allows the layout reconfiguration, with minimal effort, to meet changes in production requirements, absorbing a high level of uncertainty. The main strategies developed to cope with flexibility issues in the layout design are the dynamic, robust and reconfigurable layouts.

The dynamic and the robust layout problem concern to find a layout configuration sequence for multiple planning periods and for multiple scenarios and periods, respectively. They assume that production data for those future periods/scenarios are available and consider the costs of switching from one period to the next. These assumptions may turn the layout problem easier to solve, but are unrealistic in many situations. That is because the changes in production requirements usually are unexpected or only known slightly ahead of the next production cycle initiation, making the layout problem more complex, since it should be solved in real time mode (Meng et al., 2004).

In this context, the RLP emerges, motivated by the fact that many industries (*e.g.* consumer electronics) have lightweight workstations that can be easily moved, allowing frequent relocation. When workstations and machinery displacement is possible and can be done frequently, the layout problem is significantly simplified. However, it is known that during the relocation process certain degree of losses in production capacity is inevitable (Yamada, 2006; Ulutaş and Işlier, 2008). Thus, considering reconfiguration costs is important, since a re-layout is only viable when the system relocation costs are low (Abdi and Labib, 2003; Wang, 2011b). Additionally, the RLP addresses the transition from the current period to the next, minimising the relocation cost while maximising the potential saving in material flow and inventory costs (Meng et al., 2004).

Hence, adaptable processes, equipment and system reconfiguration are challenges that industries face to rapidly respond to market changes, needs and opportunities (Benjaafar, 2002), besides dealing constantly with big data issues of rapid decision making for productivity improvement (Lee et al., 2014). This paper carries out a systematic literature review on the RLP to identify its definition, main characteristics, the developments so far and the research gaps of this field of study.

B.2 Reconfigurable layout problem definition and main characteristics

Selecting the best layout configuration is complex and has significant impact on system performance (Zheng et al., 2013). Then, frequently changing the layout configuration is recommended to deal with manufacturing environments where a high level of uncertainty is present (Wang et al., 2009; Huang et al., 2010; Wang, 2011b). In late 90's, the RLP concept emerged to deal with the facility design in dynamic and uncertain environments (Heragu and Kochhar, 1994). A few authors have defined it as a tactical problem (Heragu et al., 2001; Meng et al., 2004; Garbie, 2014), as an optimisation problem (Xiaobo et al., 2000b; Benjaafar, 2002; Abdi and Labib, 2003, 2004b; Abdi, 2005, 2009; Dou et al., 2009a; Rak, 2009; Stamirowski and Rak, 2009) or, still, as a layout ability of being flexible, movable and changeable enough to adjust its structure due to changes in demand, product mix, volume or other requirements (Lacksonen and Chao-Yen, 1998; Kochhar and Heragu, 1999; Bruccoleri et al., 2005; Yamada, 2006; Youssef and ElMaraghy, 2006; Drira et al., 2007; Kulturel-Konak et al., 2007; Ming et al., 2007; Youssef and ElMaraghy, 2007; Sabic and Brdarevic, 2008; Ulutaş and Işlier, 2008; Wang et al., 2008; Youssef and ElMaraghy, 2008; Giordani et al., 2009; Wang et al., 2009; Dou et al., 2010; Huang et al., 2010; Keshavarzmanesh et al., 2010; Koren and Shpitalni, 2010; Abbasi and Houshmand, 2011; Wang, 2011b; Goyal et al., 2012; Guan et al., 2012; Hasan et al., 2012a; Leitao et al., 2012; Rivera et al., 2012; Benkamoun et al., 2013; Cedeno-Campos et al., 2013; Goyal et al., 2013; Jain et al., 2013; Zheng et al., 2013; Jaramillo et al., 2014; Jiang et al., 2014; Padayachee and Bright, 2014; Rabbani et al., 2014; Renzi et al., 2014; Kheirkhah et al., 2015; Kulkarni et al., 2015; Kouki Amri et al., 2016). However, it is agreed that the RLP assumes that production data are available only for current and upcoming production period and considers system operational performance.

In this paper we define RLP as the ability of the layout to rearrange frequently, with minimal effort, to adjust its configuration to new circumstances, considering system operational performance and providing the exact capacity and functionality needed, when required. It also aligns for the notion of real-time enterprise, since the changes in the layout configuration should occur rapidly and be readily available, while the production system keeps operating on the edge by doing real-time layout adjustment with live data (Meng et al., 2004; Keshavarzmanesh et al., 2010). Also, it is important to consider that during the reconfiguration process some unproductive time may exist, resulting in some loss of production capacity (Yamada, 2006; Ulutaş and Işlier, 2008).

The RLP usually aims to achieve the optimal or near-optimal layout configuration, which quickly allows resources rearrangement to respond to market changes. In addition, the layout should guarantee shorter lead times, lower inventories levels, material flow efficiency and minimum relocation cost, as well as the improvement of system capacity, functionality and performance.

Besides reconfigurability; reusability, responsiveness, adaptability, dynamicity, flexibility, reliability and modularity were considered important features to achieve a reconfigurable layout. The reusability is an economic/strategic factor that allows changing system's capacity and functionality with maximum utilisation, while changing product types. It also contributes to the system responsiveness, minimising underutilised capacity (Abdi and Labib, 2003, 2004b). Responsiveness is the system capacity to act in response of sudden changes in market, technology or regulatory requirements. Adaptability, dynamicity and flexibility deal with an existing layout capacity to rearrange quickly and frequently due to changes in the manufacturing requirements. As reusability, they are also connected to the system responsiveness. The reliability aligns to the fact that customers' demand and throughput should be achieved even when a re-layout is in progress. Lastly, modularity is mainly related to software and hardware components, but when the layout problem is focused, the RMT utilisation rises, since they are modular machines with a flexible structure that allows changes of its resources, making easier to reconfigure equipment or reorganising the plant layout. Thus, the modularity facilitates the layout rearrangement in ordinary conditions or when an exception occurs and contributes to resources relocation with minimal effort (Bruccoleri et al., 2005).

B.3 Research method and paper's categorisation

This study adopted the systematic literature review, which is a formal approach based on a replicable, scientific and transparent process to locate, select, analyse, synthesise and report evidences (Tranfield et al., 2003). Advantages of using it are many, but increased power and precision in estimating effects and risks worth to be highlighted (Mulrow, 1994).

The main search engine used was Web of Science that provides a comprehensive citation search and access to several databases. The keywords were defined to obtain scientific papers specifically related to the RLP and to what has been done to solve it. This process resulted in the selection of 60 papers for in-depth evaluation. In order to develop a descriptive analysis of those papers, the following categories were selected: journal, publication year, authors, keywords and cited papers. The analysis provides the statistics for this research area and a comprehension of those papers content.

The selected papers were also classified according to their research method. The categorisation was divided into theoretical and practical works. In the first group, there are conceptual papers and literature reviews, while the second group is composed by case studies, modelling and evaluation. The dominant approaches are case studies and modelling, representing 72% of the analysed papers.

B.4 Initial data statistics

The top 5 journals that most contributed to the RLP (Table B.1) indicates that this subject has been studied in production management area as well as in the robotics field of study.

Although the RLP concept had emerged in 1994, this work considers papers published since 1998. Figure B.1 represents the evolution of this research topic over the years, showing an increasing number of publications.

Table B.1: The top 5 most contributing journals and the number of retrieved papers.

Journal	Number of papers
International Journal of Production Research	12
International Journal of Advanced Manufacturing Technology	5
Computers & Industrial Engineering	4
Journal of Manufacturing Systems	3
Robotics and Computer-Integrated Manufacturing	2

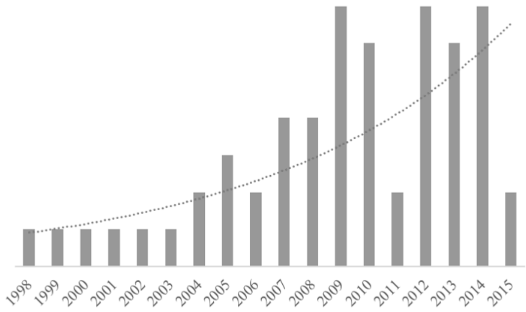


Figure B.1: Publishing trend in the RLP area.

B.5 Bibliometric analysis

Through the bibliometric analysis, which allows the identification of new fields, activities bursts, bifurcations and mergers (Barnett, 2011), the author influence (Table B.2 and Table B.3) and keywords statistics (Table B.4 and Table B.5) were identified. BibExcel was used to conduct it since this application has interaction with several databases (*e.g.* Web of Science) and software (*e.g.* Excel and Gephi) (Persson et al., 2009).

Table B.2: The top 10 contributing authors.

Author	Number of papers
Heragu S	6
ElMaraghy H	5
Dai X	3
Meng G	3
Youssef A	3
Zijm H	3
Abdi M	2
AlGeddawy T	2
Dou J	2
Labib A	2

The main results of this analysis show that Heragu S and ElMaraghy H seem to be the most contributing authors in this field of study, despite the small number of publications. A deeper examination of their background revealed that the first author has been studying the layout problem in manufacturing systems while the second has been dedicated to study manufacturing systems, in terms of providing them flexibility. Both subjects are relevant to this research topic. A complement-

Table B.3: The most relevant contributing paired authors.

Author1	Author2	Number of papers
Heragu S	Zijm H	3
Meng G	Heragu S	3
Meng G	Zijm H	3
Youssef A	ElMaraghy H	3
Adbi M	Labib A	2
AlGeddawy T	ElMaraghy H	2
Dai X	Meng Z	2
Dou J	Dai X	2
Dou J	Meng Z	2
Heragu S	Zijm H	2

Table B.4: The most frequently used words in papers title.

Word	Frequency
system	27
manufacturing	24
reconfigurable	23
layout	15
configuration	10
approach	10
design	9
facility	7
optimisation	6
dynamic	5

Table B.5: The most relevant keywords.

Keyword	Frequency
RMS	20
genetic algorithm	5
Mconfiguration selection	3
facility layout	3
machine selection	3
optimisation	3
configuration generation	3
layout design	3
RMT	3
simulation	3

ary analysis of the paired-author contribution (Table B.3) enhances the existence of a research group who focuses on the RLP, in which all the most contributing authors appear. In addition, the small number of influential articles indicates the need for more active research.

In total, 162 different words were considered for paper's title analysis and 122 keywords were counted. When comparing the most used words in paper's title (Table B.4) with the most associated keywords (Table B.5), it is possible to note the consistence among them and that the 3 most used

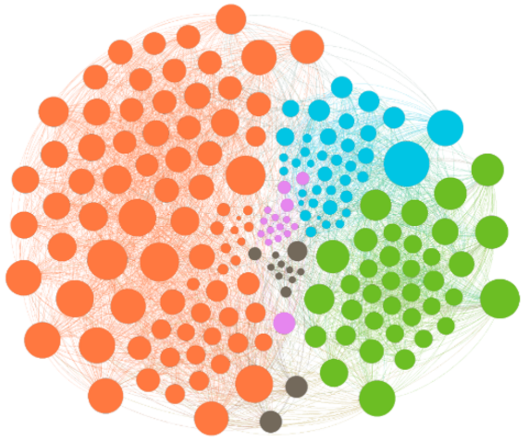


Figure B.2: The Force Atlas layout with the 5 clusters representation.

words in paper's title composes the most used keyword. Besides, the solutions proposals may appear as a keyword. Therefore, it seems that genetic algorithms and optimisation models have been the most used methods to solve the RLP.

B.6 Network analysis

The Gephi software was used to conduct a network analysis for the selected sample, due to its functionality for graph analysis and patterns identification. Also, a citation and co-citation analysis were made to investigate the connectivity degree between the papers identified in the systematic literature review, considering only the papers that were cited at least two times. The top 10 most referred papers were (Rosenblatt, 1986; Kusiak and Heragu, 1987; Montreuil and Venkatadri, 1991; Kouvelis et al., 1992; Lee, 1997; Koren et al., 1999; Mehrabi et al., 2000a; Xiaobo et al., 2000b; Abdi and Labib, 2003; Meng et al., 2004), showing their relevance for this field of study.

As result of the network analysis, a co-citation map was established, revealing a 183-node co-citation network. This map is composed by nodes (papers) and edges (paper's co-occurrence). If two publications appear together in the reference list of more than one paper, they are considered co-cited (Hjørland, 2013). At first, Gephi randomly locates the nodes, but it offers several algorithms to create different layouts. Force Atlas was chosen due to its simplicity and readability (Bastian and Heymann, 2009). In this layout, the most connected nodes move to the network centre while the nodes less connected move to the borders. The more edges are included, the bigger are the nodes.

The co-citation network also allows data clustering, which has been used in many domains as a classification tool for grouping a given publications set and to investigate community structures in networks. A cluster is a group of well-connected publications that have limited connection to publications in other clusters. The nodes may become a cluster where the connection (weight of edges) is greater between the nodes of the same cluster than when compared to those of different clusters (Radicchi et al., 2004). A default tool in Gephi, based on the Louvain algorithm, was used to identify the clusters of the 183-node co-citation network, establishing 5 clusters. Figure B.2 shows the interaction and the clusters' positions.

B.7 Content analysis of clusters

Based on the papers that compile these 5 clusters, it is possible to define the main research areas, since the papers that are more often co-cited tend to be in the same or in similar areas (Hjørland, 2013). The papers contained in cluster 1 have been published since 1975. The earliest papers introduced the concepts of modularity, adaptability and reconfigurability, connecting them to manufacturing systems and its components. Only in late 90's a proper definition of a RMS was made (Koren et al., 1999). After that, this type of production system was related as the "key to future manufacturing" (Mehrabi et al., 2000a). From 2002, the concept of RMT emerged, also the RMS paradigms and the layout design in dynamic environments started to be researched.

Cluster 2 is composed by papers that deals with the traditional layout problem (dynamic and robust), considering restricted or varying areas, multi-floors and other criteria. A few papers have concerned the layout design in changing environments, research challenges and trends. Among the used approaches are heuristics, quadratic assignment algorithms and simulated annealing.

The papers contained in cluster 3 deals with heuristics and meta-heuristics in the facility layout design. The leading papers considered dynamic/changing environments and presented a layout performance analysis. It worth to highlight that (Meng et al., 2004) seems to be the starting point of the RLP research. Cluster 4 includes papers that concerned postponement strategies such as delayed product differentiation as an attempt to simplify the system layout design. Finally, the cluster 5 leading paper presented a decomposition approach to design manufacturing systems. The other articles of this cluster have shown a layout performance analysis, considering productivity and convertibility measures. The number of papers, the main articles and the research focus of each cluster are shown in Table B.6.

Table B.6: The number of papers, the main papers and the research focus of each cluster.

Cluster	Number of papers	Main papers	Research focus
1	70	Lee (1997); Mehrabi et al. (2000a); Abdi and Labib (2003, 2004b); Koren and Shpitalni (2010)	Development of models and strategies to design a RMS
2	53	Rosenblatt (1986); Kouvelis et al. (1992); Conway and Venkataramanan (1994); Benjaafar (2002)	Proposals to solve the traditional layout problem
3	36	Braglia et al. (2003); Meng et al. (2004)	Facility layout design using heuristics and meta-heuristics
4	13	Bragg (2004)	Postponement strategies to design the facility layout
5	11	Cochran et al. (2002)	Decomposition approach to manufacturing system design

Therefore, besides the fact that the 5 leading papers of cluster 1 are among the top 10 cited papers, the research focus confirms that the cluster 1 tends to be the most relevant group of papers for this research topic, although no cluster focused exclusively in the RLP. As consequence, further investigation is needed to fulfil this gap.

B.8 Methodology and methods analysis

Among case studies, modelling and evaluations, it seems that optimisation models, meta-heuristics, heuristics and hybrid methods are the main approaches suggested to solve the RLP (Table B.7). Mixed integer programming was the optimisation model most applied (Lacksonen and Chao-Yen, 1998; Abbasi and Houshmand, 2011; Niroomand et al., 2014; Rabbani et al., 2014), while the genetic algorithm was the most used meta-heuristic (Kochhar and Heragu, 1999; Meng et al., 2004; Youssef and ElMaraghy, 2006, 2007, 2008; Wang et al., 2008; Dou et al., 2010; Abbasi and Houshmand, 2011; Wang, 2011b; Jiang et al., 2014) and the open queuing network model the most used heuristic (Heragu et al., 2001; Meng et al., 2009). Those methods' potential can be exploited in further studies.

Table B.7: Summary of solution methods applied to case studies, modelling and evaluation.

Type	Solution methods			
	optimisation model	meta-heuristics	heuristics	hybrid approach
case study	Dou et al. (2009b) AlGeddawy and ElMaraghy (2010a) AlGeddawy and ElMaraghy (2010b)	Kochhar and Heragu (1999) Youssef and ElMaraghy (2006) Youssef and ElMaraghy (2007) Youssef and ElMaraghy (2008) Wang et al. (2008) Dou et al. (2010) Huang et al. (2010) Leitao et al. (2012)	Meng et al. (2004) Bruccoleri et al. (2005) Ming et al. (2007) Rivera et al. (2012) Garbie (2014)	Sabic and Brdarevic (2008) Wang et al. (2009) Keshavarzmanesh et al. (2010) Wang (2011b) Andrisano et al. (2012)
modelling	Lacksonen and Chao-Yen (1998) Xiaobo et al. (2000b) Giordani et al. (2009) Koren and Shpitalni (2010) Hasan et al. (2012a) Cedeno-Campos et al. (2013) Goyal et al. (2013) Zheng et al. (2013) Jaramillo et al. (2014) Niroomand et al. (2014) Rabbani et al. (2014)	Yamada (2006) Bensmaine et al. (2013) Goyal et al. (2012) Kheirkhah et al. (2015)	Heragu et al. (2001)	
evaluation	Guan et al. (2012) Padayachee and Bright (2014)	Kulturel-Konak et al. (2007) Abbasi and Houshmand (2011)	Qiu et al. (2005) Meng et al. (2009)	Ulutaş and Işlier (2008)

In general, we can conclude that the RLP objective function is determining the optimal or near optimal layout configuration, but it could consider minimising costs, maximising rates, profits or other factors, depending on the manufacturing environment. Additionally, many decision variables have been considered in the problem formulation, *e.g.* area, demand, batch size, distance between machines, resources/stations number, ramp-up time, cell sizes, operational capacity, immovable machines and costs, mainly material handling costs and relocation costs. Besides, all RLP had some constraints, such as operations sequence or precedence, space for reconfiguration, layout feasibility, unproductive time, departments or machines size and shape, machine capacity, stationary facilities, non-overlapping departments and empty spaces. As consequence of the utilisation of many decision variables and constraints, several combinations are possible, resulting in many opportunities for future studies.

All conceptual papers described the facility layout problem, its formulation and solutions developed so far (Benjaafar, 2002; Kouki Amri et al., 2016), while literature reviews addressed a technical analysis and have suggested directions for further research (Drira et al., 2007; Rak, 2009;

Stamirowski and Rak, 2009; Bensmaine et al., 2013; Jain et al., 2013; Renzi et al., 2014; Kulkarni et al., 2015). However, all of them agree that there is a need for more flexible, modular and easily reconfigurable layouts, to adapt quickly to changes in production requirements, after each production period. It was also pointed that the layout problem can be formulated as: discrete; continuous; fuzzy or multi-objective. The most common solution approaches are GA, MIP, PSO, SA, ACO, heuristic algorithm, neural network and TS.

The key conclusions that can be extracted from those papers are that maximising operational performance is more important than minimising material handling costs (Benjaafar, 2002); the reconfigurability paradigm and existing methodologies should be considered to develop new strategies that consider all costs and efforts related to system reconfiguration (Stamirowski and Rak, 2009; Rak, 2009; Bensmaine et al., 2013); the use of 3D, graphical tools and approaches such as PSO, ACO and artificial intelligence (AI) worth more research to be applied to RMS design, as well as considering risks in the problem formulation (Drira et al., 2007; Jain et al., 2013; Renzi et al., 2014; Kulkarni et al., 2015; Kouki Amri et al., 2016). Therefore, those are others opportunities for future studies.

B.9 Conclusion

This paper presented a structured literature review about the RLP, establishing it as an important research area. Firstly, the literature was exploited to identify the existing definitions of the RLP and its main features. After, the key contributing authors and journals, the clusters and the main methodological approaches were presented and explored. Finally, an in-depth analysis of the selected sources allowed the identification of trends and gaps. There is available space to the development of hybrid methods (*e.g.* combining meta-heuristics and heuristics) and new strategies, which consider all costs and efforts associated to system reconfiguration, as well as the use of PSO, ACO and AI to resolve the RLP. Graphical tools and available technology (*e.g.* robotics) may contribute to develop reconfigurable tools and to layout design. Also, considering system operational performance, risk management and reliability measures in the objective function are possibilities for further studies.

However, this study has a few limitations. The bibliometric and the network analysis were conducted to generate insights and to present an objective review of the RLP, identify key papers and key investigators, but they do not provide an interpretation of the papers content or an explanation of their importance to the scientific field. Additionally, the author statistics may not be an effective approach to evaluate the published papers quality, but it can be seen as a positive relation between the quantity and the quality of the key papers. The keywords used in the search were defined to guarantee this study effectiveness, restricting the results to the RLP. As consequence, different keywords utilisation may result in a more embracing literature review.

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