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Dissertação para a obtenção do grau de Mestre em Engenharia e Gestão Industrial

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To my wife and son

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Abstract

The concept of reconfigurable manufacturing systems (RMSs) emerged as a strategy to achieve more responsive manufacturing systems, capable of adjust the functionality and capacity when required. This topic is a current issue to manufacturing companies because the feasibility of RMSs was achieved recently due to the novel technologies promoted by the Industry 4.0. In RMSs, the reconfigurability is the ability that allows changes from one product to another, the addition or removal of resources, with minimal effort and without delay. For this reason, the level assessment of the reconfigurability is of utmost importance to industries.

The objective of this research is to describe the development of a reconfigurability index (RI) that can be used by companies to define how reconfigurable their manufacturing systems are. Specifically, this study aims to determine the extent to which each core characteristic contributes to the composition of the reconfigurability index and the current level of reconfigurability present in Portuguese companies. Additionaly, this work tries to establish a relationship among the core characteristics and the operational performance of manufacturing systems, and the extent to which each core characteristic is implemented in different industrial sectors.

To build the RI, data from a questionnaire survey was used to select the variables and a principal component analysis (PCA) was applied to the survey results to determine the contributions of the core characteristics. The RI was used to establish a ranking of the industrial sectors of respondent companies and to discuss the implementation level of the core characteristics of reconfigurability.

The findings show that each core characteristic contributes with a different amount to the composition of reconfigurability. Adaptability and diagnosability contribute the most, with 25% each. Portuguese companies have a moderate level of reconfigurability implemented. Regarding the operational performance, with basis on the literature on reconfigurability, modularity seems to contribute to quality and delivery; integrability to delivery and flexibility; adaptability to cost and quality, and diagnosability to quality and delivery. However, just the influence of integrability on delivery and of adaptability on cost are supported statistically. Among the industrial sectors, the reconfigurability varies from low to moderate levels.

Keywords: Reconfigurable manufacturing system; reconfigurability index; reconfigurability level assessment; principal component analysis.

Resumo

O conceito de sistemas de produção reconfiguráveis (SPRs) surgiu como uma estratégia para alcançar sistemas de produção mais ágeis, capazes de ajustar a funcionalidade e capacidade quando necessário. Este tópico é um problema atual para empresas porque a viabilidade de SPRs foi alcançada recentemente devido às novas tecnologias promovidas pela Indústria 4.0. Em SPRs, a reconfigurabilidade é a capacidade que permite a mudança de um produto para outro, a adição ou remoção de recursos, com mínimo esforço e sem demora. Por esta razão, a avaliação do nível de reconfigurabilidade é de extrema importância para as indústrias.

O objetivo desta pesquisa é descrever o desenvolvimento de um índice de reconfigurabilidade (RI) que pode ser utilizado por empresas para definir o quão reconfiguráveis são seus sistemas de manufatura. Especificamente, este estudo pretende determinar em que medida cada característica fundamental contribui para a composição da reconfigurabilidade e o nível atual de reconfigurabilidade presente nas empresas portuguesas. Adicionalmente, este trabalho tenta estabelecer uma relação entre as características essenciais e o desempenho operacional dos sistemas de manufatura, e a extensão em que cada característica básica é implementada em diferentes setores industriais.

Para construir o IR, uma pesquisa por questionário foi usada para selecionar as variáveis e uma análise de componentes principais (ACP) foi aplicada aos resultados da pesquisa para determinar as contribuições das características centrais. O IR foi usado para estabelecer um ranking dos setores industriais das empresas respondentes e para discutir o nível de implementação das características centrais de reconfigurabilidade.

Os resultados mostram que cada característica central contribui com uma quantidade diferente para a composição da reconfigurabilidade. A adaptabilidade e a diagnosticabilidade são as que mais contribuem, com 25% cada. As empresas portuguesas têm um nível moderado de reconfigurabilidade implementado. Em relação ao desempenho operacional, a modularidade parece contribuir para a qualidade e entrega; integrabilidade para entrega e flexibilidade; adaptabilidade para custo e qualidade e capacidade de diagnóstico para qualidade e entrega. Entre os setores industriais, a reconfigurabilidade varia de níveis baixos a moderados. A implementação das características centrais variam significativamente, mas o RI parece estar relacionado aos níveis de flutuações do mercado.

Palavras-chave: Sistema de produção reconfigurável; índice de reconfigurabilidade; avaliação do nível de reconfigurabilidade; análise de componentes principais.

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Acronyms

ACP Análise de componentes principais.

AHP Analytic hierarchy process.

ANP Analytic network process.

BOM Bill of materials.

CFA Confirmatory factor analysis.

DPLs Dedicated production lines.

ETO Engineering to order.

FMSs Flexible manufacturing systems.

IR Índice de reconfigurabilidade.

ISIC International standard industrial classification of all economic activities.

KMO Kaiser-Meyer-Olkin.

MCDA Multi-criteria decision analysis.

MTO Make to order.

MTS Make to stock.

PCA Principal components analysis.

PROMETHEE Preference ranking organisation method for enrichment evaluation.

RI Reconfigurability index.

RMSs Reconfigurable manufacturing systems.

SPRs Sistemas de produção reconfiguráveis.

Chapter 1

Introduction

1.1 Background

At the end of 1990's, the concept of reconfigurable manufacturing systems (RMSs) emerged aiming at achieving more responsive production systems, capable of manufacture high quality products at low costs. Such systems are designed to adjust their production capacity and functions quickly, through reconfigurability, to respond to unpredictable changes in the production requirements. Thus, the RMSs are vital to deal with situations in which productivity and responsiveness are indispensable [1].

Even though the RMSs were introduced 20 years ago, the implementation potential was achieved recently, due to the novel technologies promoted by the Industry 4.0 paradigm [2, 3]. This means that, in an industrial environment where manufacturing system are required to be more and more effective to answer suddenly changes in production demand and volume, RMSs can be adopted as a strategy to meet these fluctuations rapidly, with a significant cost benefit [1].

The reconfigurability is an essential ability of RMSs [4–6]. At the operational level, the reconfigurability can be understood as the ability to reorganise the production components to adjust the manufacturing system to new environmental and technological situations [7]. At the tactical level, the reconfigurability can be seen as an engineering characteristic that deal with the design of systems and machines in order to obtain customised products [8]. To enable the reconfigurability, manufacturing systems must have some core characteristics such as modularity, integrability, customisation, convertibility, scalability and diagnosability [1, 5].

In general, the studies on RMSs can be divided in five main research lines [9]:

1) *Reconfigurability level assessment*, which consists in the development of reconfigurability metrics;

2) *Analysis of RMSs features*, that means the study of the core characteristics of reconfigurability, such as modularity, integrability, customisation, convertibility, scalability and diagnosability;

3) *Analysis of RMSs performances*;

4) *Applied research and field applications*, i.e., case studies of real companies; and

5) *Reconfigurability toward Industry 4.0 goals*, that establish the relationship between RMSs and the novel technologies.

This work aims to contribute to the first research line. To evaluate the level of reconfigurability present in industries, the existing works refer, mainly, to empirical studies or construction of indices. Despite the significant contributions, the majority of studies adopts multi-criteria decision techniques, in which the choice of weights for each criterion is subjective. This means that the results obtained from this technique do not have general validity, due to the dependence of a specific case. Therefore, accurate and quantitative indices are needed [9].

For this reason, this research adopts the principal component analysis (PCA), that has been used to derive weights and build indices [10, 11]. The PCA has some advantages over the traditional methods, because it allows the derivation of factors from a large number of variables [12].

1.2 Objectives

This is an exploratory study, which objective is to build an index to assess the level of reconfigurability present in manufacturing companies. Specifically, the study aims to:

- Use PCA to define the weights for the five core characteristics of reconfigurability: modularity, integrability, customisation, adaptability and diagnosability.

In addition, this study shows the utilisation of the index to establish a ranking of the companies surveyed, according to their international standard industrial classification of all economic activities (ISIC) code, analyses the implementation of the core characteristics of reconfigurability in the industrial sectors and investigates the relationship among the implementation level of the core characteristics and the operational performance.

1.3 Research questions

The following research questions guide the development of this thesis and the aforementioned objectives:

1) To what extent each core characteristic contributes to the composition of reconfigurability?

2) What is the current level of reconfigurability present in Portuguese companies?

3) Is there a relationship among the core characteristics and the operational performance?

4) What is the implementation level of reconfigurability and to what extent each core characteristic is implemented in the industrial sectors?

1.4 Methodology

The questionnaire survey and the data collected by [13] were used to select the variables and build the reconfigurability index (RI). The objective of the survey is to identify the implementation level of each core characteristic in industries.

Considering the need to develop accurate quantitative indices to assess the reconfigurability, a PCA with orthogonal rotation (varimax) was applied to the survey results to determine the contribution, i.e., the weights, of the core characteristics to the composition of reconfigurability. These weights are the basis to calculate the index proposed.

To determine the ranking of the industrial sectors surveyed, the index was calculated for each respondent company, which were then grouped in accordance to their ISIC code. After that, the implementation levels of the core characteristics were analysed. Finally, this study conducts an analysis to verify the relationship between the RI and the operational performance of manufacturing companies, whether any.

1.5 Document structure

To better understand this work, it is important to know the concept, characteristics and benefits of RMSs. Thus, chapter 2 presents a literature review on this topic (section 2.1). Besides, this chapter describes the reconfigurability, which is a vital ability of RMSs (section 2.2), including relevant works on the development of reconfigurability metrics. Lastly, this chapter shows different methods of weighting and aggregating and explains why the PCA was chosen to develop the RI (section 2.3).

Chapter 3 begins to describe the questionnaire survey, i.e., the measurement instrument, as well as the characterisation of the sample (section 3.2). The full questionnaire can be found in annex I. The PCA, that was used to calculate the weights of the core characteristics and build the RI, is also detailed in this chapter (section 3.3).

The outcomes are also presented and discussed in chapter 3, that shows and analyses the RI value for sampled companies (section 3.4), based on the five core characteristics: modularity, integrability, customisation, adaptability and diagnosability; and the ranking of the industrial sectors surveyed (section 3.5). The empirical study ends with an analysis of the operational performance compared to the RI (section 3.6).

Finally, chapter 4 summarises the main conclusions of the research, presents the limitations and suggests some directions for future studies.

Chapter 2

Literature review

2.1 Reconfigurable manufacturing systems

The increase in the frequency of the introduction of new products, changes in parts of existing products, demand, product mix, government requirements and process technologies are driven by aggressive economic competition on a global scale and by increasingly demanding customers, and occur at an increasingly fast pace. To face this volatile and unpredictable market, organisations need to be able to cope to changes rapidly and economically [1, 2, 6].

In this context, it is possible to state that production systems have evolved from job-shops to dedicated production lines (DPLs), flexible manufacturing systems (FMSs) and RMSs. Job-shops use generic machines, low volumes, high variety and significant human involvement. DPLs work with high volumes and low variety, and are driven by economies of scale. FMSs refer to mass customisation. Such systems have a greater capacity to respond to changes in products, production technology and markets, as they were developed to meet the needs of medium volume production. RMSs, in turn, emerged in an attempt to achieve changes in the functionality and capacity of manufacturing systems, where resources can be added, removed, modified or exchanged whenever necessary [14].

For this purpose, RMSs combine the high production rates of DPLs and the flexibility of FMSs, through [1]:

- An adjustable structure for the system and its resources, which allows system's scalability and adaptability to changes in demand and the introduction of new products, respectively.

- The system design around a product family, with the necessary flexibility to manufacture all products in this family.

Table 2.1 summarises the main characteristics and differences among DPLs, FMSs e RMSs.

Table 2.1: The main characteristics of DPLs, FMSs e RMSs

Characteristics	DPLs	FMSs	RMSs
Machine structure	Fixed	Fixed	Adjustable
System focus	Part	Machine	Part family
Scalability	No	Yes	Yes
Flexibility	No	General	Customised

Source: [1]

In the last two decades, many works have been developed on RMSs, including recent and comprehensive literature reviews [9, 15]. Most of these studies involve the design and operation of RMSs. Specifically, studies on the design of RMSs include the development of methodologies, economic evaluation of reconfigurability, design of reconfigurable machines, the characteristics of reconfigurability and their implementation, and the identification and modelling of reconfigurability. The research on the operation of RMSs includes the generation of process plans, configuration selection, reconfiguration and scalability planning [3].

In sum, the research in the area of RMSs can be classified in the following streams, summarised in figure 2.1 [9] and table 2.2.

1. *Reconfigurability level assessment*. This stream is dedicated to assess the reconfigurability level of manufacturing systems using metrics that provide quantitative data for the evaluation of the RMSs.

2. *Analysis of RMSs features*. This perspective studies the reconfigurability core characteristics: modularity, integrability, customisation, diagnosability, convertibility and scalability. Other characteristics such as mobility, universality, compatibility, availability and sustainability are rarely mentioned.

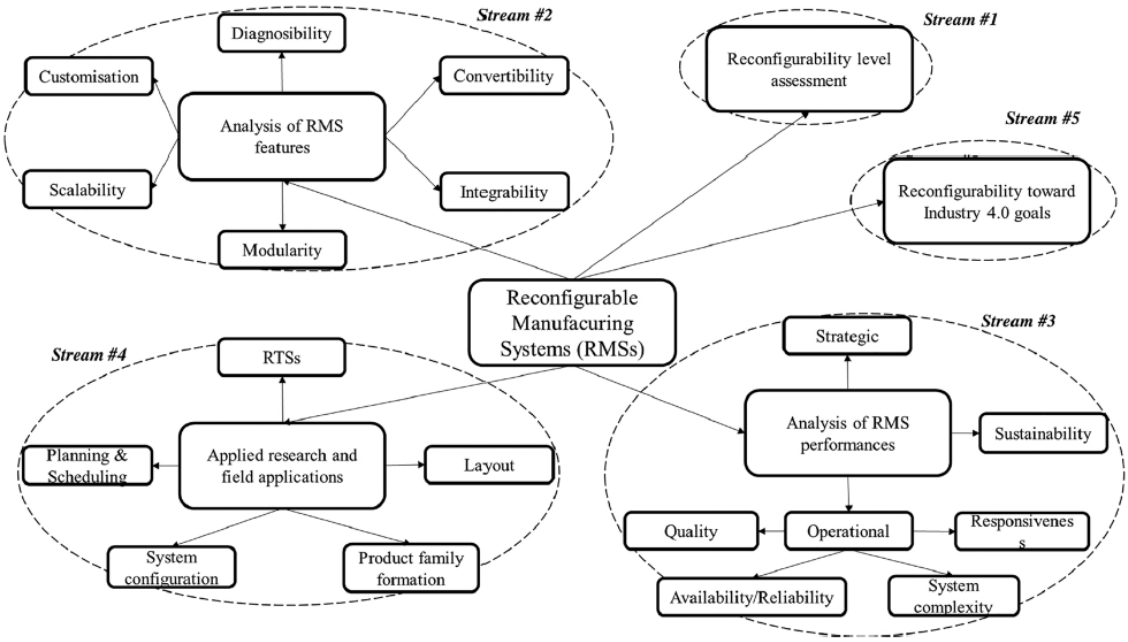
3. *Analysis of RMSs performances*. This research line deals with the performance of RMSs from the managerial strategy (high levels) to the operational strategy (daily activities).

4. *Applied research and field applications*. This stream works in the area of layout problems, reconfigurable transport systems, product family formation, the development of reconfigurable cellular production systems and the planning and sequencing problem of RMSs.

5. *Reconfigurability toward Industry 4.0 goals*. This research line focuses on studying the impact of technologies promoted by Industry 4.0 on the RMSs.

Two main reasons explain the study of RMSs 20 years after their introduction: sustainability and implementation feasibility, due to new technologies. Regarding sustainability,

Figure 2.1: Schematic of RMSs research perspectives



Source: [9]

Table 2.2: Summary of the main works in each RMSs stream

Stream	Description	References
1	Reconfigurability level assessment	[16], [17], [8], [18], [19]
2	Analysis of RMSs features	[5], [9], [20], [1], [6], [21], [22]
3	Analysis of RMSs performances	[23], [24]
4	Applied research and field applications	[25], [26]
5	Reconfigurability toward Industry 4.0 goals	[2], [27]

Source: the author

RMSs have better environmental and economic performance, as well as reduced energy consumption [9]. The RMSs are a strategy to achieve sustainable production, as they are capable of producing several generations of products [28, 29]. Regarding technologies, those promoted by Industry 4.0 can facilitate the design, operation and implementation of RMSs [2, 3]. In addition, the implementation of RMSs is still an open question for industries. This is because efficient approaches are required for the RMSs design, which are aligned with the practical aspects of the market, incorporating all the characteristics of reconfigurability and its performance measures [15].

2.2 Reconfigurability

2.2.1 Definition

Reconfigurability is the vital feature of RMSs. Initial studies on reconfigurability classify it as a type of 'changeability'. In this case, reconfigurability is defined as the ability to change the behaviour of a manufacturing system through changes in its configuration (*hardware*). This implies changing, with minimal effort and without delay, from one product (or product family) to another (or others), adding or removing productive resources [14].

Other studies affirm that reconfigurability can be implemented at several levels, such as factory, system and workstation levels [13, 30]. For this reason, a more appropriate and generic definition of reconfigurability is 'the ability to change and reorganise components of a manufacturing system economically' [6].

Many authors consider that reconfigurability is enabled by a set of six characteristics: modularity, integrability, customisation, scalability, convertibility and diagnosability [1, 6, 19]. These characteristics are summarised in table 2.3.

Table 2.3: Core characteristics that enable reconfigurability

Characteristic	Description	Reference
Modularity	It must ensure that production equipment consists of modules that can be easily rearranged, added or removed from the shop floor to adapt the configuration of the manufacturing system	[1]
Integrability	It represents the integration of new technologies or equipment in the existing manufacturing system, as well as the existence of an integrated control protocol	[17]
Customisation	The purpose of customisation is to design the manufacturing system based on a product family, which has the exact control functions required	[1]
Scalability	This is the ability to easily modify production capacity, changing system components in response to changes in demand	[20]
Convertibility	Convertibility is the system's ability to adjust production functionality or change from one product to another in response to dynamic market changes	[1]
Diagnosability	It includes inspection features that allow the detection of failures or quality problems in real time	[31]

Source: adapted from [24]

Six fundamental principles, based on the six characteristics, must be taken into account when designing RMSs [1]:

1. The system capacity must be adaptable, in terms of costs, to the demand of future markets.

2. The system must be designed to be adapted to possible new products required by customers.

3. The RMSs must have an optimal inspection system built in.

4. The system must be designed around a product family.

5. Maximise productivity by reconfiguring operations and allocating tasks to machines.

6. Maintenance must be carried out in order to increase the reliability of machines and optimise the production rate of the system.

Several empirical studies have investigated the reconfigurability level present in industries [4, 5, 22, 32]. Others considered the core characteristics to assess the reconfigurability, as shown in table 2.4.

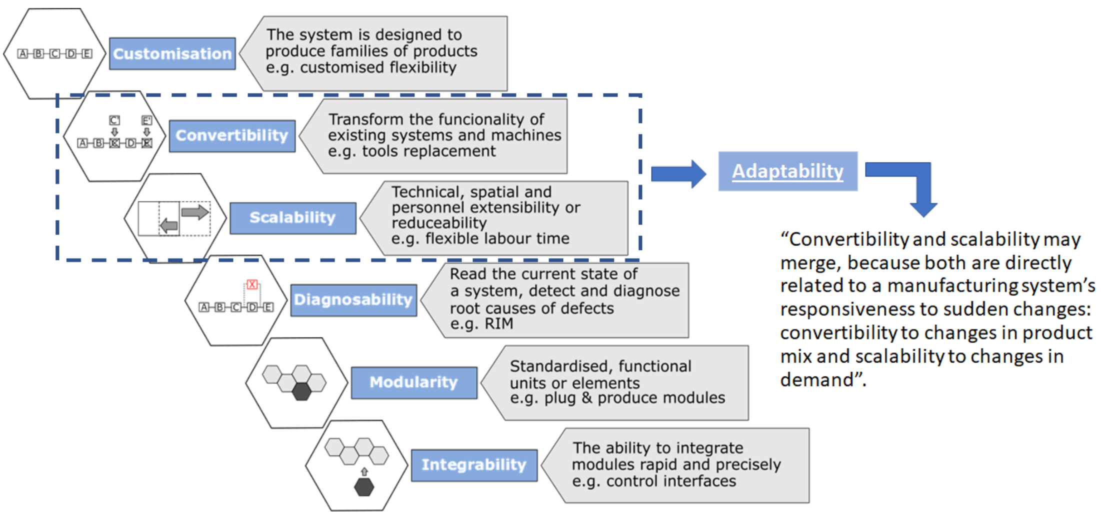
Table 2.4: Core characteristics used for reconfigurability assessment.

Reference	Modularity	Integrability	Customization	Scalability	Convertibility	Diagnosability
[8]	x			x	x	x
Farid [17]	x	x	x		x	
[33–35]					x	
[19]	x	x	x	x	x	x
[6]	x	x	x	x	x	x
[4, 24, 36]	x	x	x	x	x	x
[16]	x	x	x		x	x
[37]	x	x	x	x	x	x

Source: adapted from [37].

One of these studies showed that industries recognise five characteristics of reconfigurability instead of six; scalability and convertibility are interpreted as a single characteristic, called adaptability [4]. This is represented in figure 2.2.

Figure 2.2: Summary of the core characteristics of reconfigurability



Source: Adapted from [13]

Reconfigurability metrics have also been developed to determine the readiness of a production system to change its configuration. Such metrics consider the core characteristics of reconfigurability or other criteria, at the machine or system level [15]. The most relevant studies in this area are detailed in section 2.2.2.

2.2.2 Metrics

Open challenges in the reconfigurability level assessment deal with mapping the manufacturing systems attributes and the adoption of more rigorous metrics. To this purpose, accurate and quantitative reconfigurability indices are still missing [8, 9, 33].

In order to identify existing works referred to reconfigurability metrics, a bibliographic search was conducted in the Web of Science database. The strings used were *reconfigurability* AND *index*, in the title field. However, this search returned only two results [8, 18]. In order to expand the analysis, a new search was conducted, using the strings *reconfigurability* AND *assessment*. This search returned only one result [16]. A third search was conducted, using the strings *reconfigurability* AND *measur**. This search returned six results, from which three were not related to the aim of this work and one was duplicated. These results emphasise the need for more investigation regarding the reconfigurability level assessment.

Trying to better explore the existing research on reconfigurability level assessment, this study consulted the work of [9] who conducted a exhaustive literature review on RMSs. The authors concluded that the research on reconfigurability metrics can be divided in two main groups:

1. RMSs assessment through the definition of global reconfigurability indices.
2. Mapping the manufacturing system capabilities, providing a set of metrics composed by the core characteristics of reconfigurability.

Global indices are those that consider criteria such as: the smoothness of the reconfiguration [38]; responsiveness, operational capacity, machine reconfigurability and costs [33–35, 39–42]; reconfigurability efforts [43–45]; sustainability [46]; technology, people, management and production strategy [47].

However, these studies do not include the core characteristics of reconfigurability. Considering them is essential to measure reconfigurability properly, as the effectiveness of RMSs depends on the implementation of the core characteristics [25].

Among the studies that consider the core characteristics of reconfigurability (see table 2.5), [8] mapped the characteristics of modularity, scalability, convertibility and diagnosability, using the multi-attribute theory to develop a reconfigurability index. [19] proposed quantitative models for each of the six core characteristics of reconfigurability, adopted by the majority of authors. These models were considered to determine a reconfigurability index using the analytical hierarchy process (AHP), to assign the weights to each of them.

Table 2.5: Summary of works of the second group

Reference	Characteristics	Method
[17]	Integrability, customisation and convertibility	Axiomatic project
[8]	Modularity, scalability, convertibility and diagnosability	Multi-attribute theory
[48]	Modularity, convertibility and diagnosability	Weighted sum theory
[19]	Modularity, integrability, customisation, scalability, convertibility and diagnosability	AHP and PROMETHEE
[37]	Modularity, integrability, customisation, scalability, convertibility and diagnosability	Multi-attribute theory

Source: the author

[17] considered the characteristics that drove qualitative and intuitive design of technological advances: integrability, convertibility and customisation, discussing how these characteristics fit the requirements for reconfigurability measures. [48] used the weighted sum theory to map the characteristics of modularity, convertibility and diagnosability to develop a reconfigurability index. [37] built an index of reconfigurability in supply chain based on multi-attribute theory in order to choose the most reconfigurable configuration.

Despite their contributions, these works do not have well-defined or standardised aspects. This is because they consider three, four or six core characteristics. Most importantly, these studies seem to ignore the dependence that exists between the core characteristics and the impacts that they may have on each other. Such relationships must be considered in the development of a reconfigurability index [2, 18].

In addition, all of them adopt multi-criteria decision analysis (MCDA) to develop models and methods for evaluating reconfigurability. The MCDA are able to assess conflicting criteria, supporting managers in decision making. These techniques include the steps of criteria selection, criteria weighting, evaluation and final aggregation. However, the choice of weights to be assigned to the criteria is subjective [9].

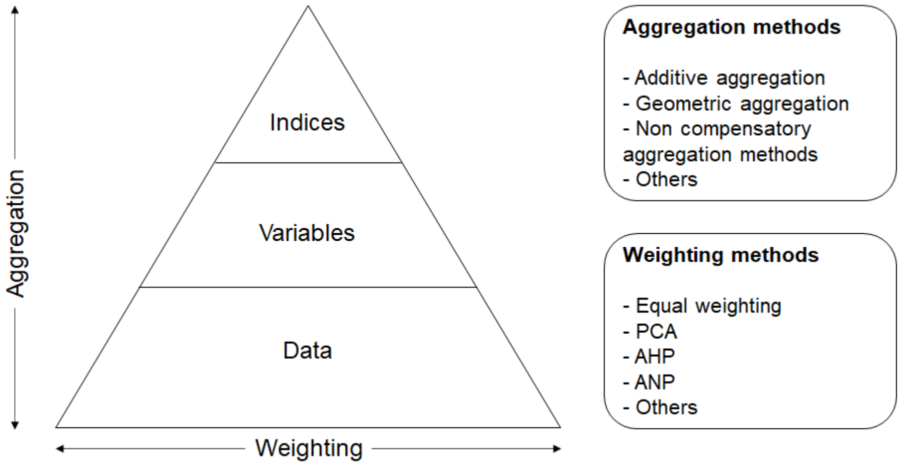
2.3 Methods for weighting and aggregating indices

Weighting and aggregation are key steps to build a RI, as they are the processes by which reconfigurability core characteristics are transferred from variables to characteristics and then from characteristics to index.

Weighting refers to the "explicit significance" that is attributed to each criterion in an index. Specifically, a weight may be considered as a kind of coefficient that is attached to a criterion, exhibiting its significance relative to the rest of the criteria. In addition, it relates the implicit significance of the attributes, as this is shown by the "trade-off" between the pairs of criteria in an aggregation process [49].

An illustration of the relationship between weighting and aggregation methods is presented in figure 2.3.

Figure 2.3: An illustration of the relationship between weighting and aggregation methods.



Source: adapted from [50].

Even though various methods for weighting and aggregating exist, each method has strengths and weaknesses. Some common methods for index weighting are equal weighting, AHP and PCA. On the other hand, some common aggregation methods are additive aggregation, geometric aggregation and non-compensatory aggregation. These methods are discussed below.

2.3.1 Weighting methods

2.3.1.1 Equal weighting

Equal weighting is a simple strategy used when all the variables are considered equally important or when no statistical or empirical evidence support a different scheme [50]. There are many justifications for choosing equal weights, including: a) simplicity of construction, b) a lack of theoretical structure to justify a differential weighting scheme, c) no agreement between decision makers, d) inadequate statistical and/or empirical knowledge, and, finally, e) alleged objectivity.

This strategy was used to calculate an aggregated measure of reconfigurability in different business production strategies [36] and a reconfigurability index [48]. However, this method has caused controversies, most of which focus on the validity and transparency of indices [50].

Choosing equal weights due to the simplicity of the construction instead of an alternative scheme that is based on a proper theoretical and methodological framework, bears a huge oversimplification cost. Furthermore, conceptually, equal weights miss the point of differentiating between essential and less important variables by treating them all equally. Considering equal weights as an “objective” is disputable. Some authors claim that equal weighting is wrong and an equally “subjective judgement” to other arbitrary weighting schemes in existence [49].

2.3.1.2 Analytic hierarchy process

AHP is a structured technique for multi criteria decision making based on pairwise comparisons of alternative elements. In this technique, the first step is to translate a complex problem into a hierarchical structure consisting of an overall goal. The second step requires comparisons in a pairwise fashion of each cluster pertaining to the same level in the hierarchy. The third step is to calculate the relative weights of variables from the comparison matrix using a eigenvector technique [51].

The weights elicited with the AHP are less prone to errors of judgement. This happens because, in addition to setting the weights relatively, a consistency measure is introduced ("inconsistency ratio"), assessing the cognitive intuition of decision makers in the pairwise comparison setting [49].

The AHP and other multi criteria decision making techniques, such as multi-attribute theory, have been used to assess the reconfigurability present in manufacturing systems, even though they do not consider the relationship that may exist among the variables [8, 19, 37]. In such case, the analytic network process (ANP) would be more appropriated, since it is applied when the decision making process cannot be structure hierarchically and involves the interaction and dependence of higher and lower level elements in a hierarchy [52]. [18] proposed a RI using the ANP, but the work lacks empirical evidence.

Although the criteria weights are often obtained by directly surveying stakeholders, less rigorous surveys may not accurately reflect the true preferences. However, rigorous stakeholder preference elicitation are expensive. A more sophisticated method will provide valuable results for larger data sets with better influencing factors and data quality. Also, despite the popularity as a technique to elicit weights, on the occasion that the number of indicators is very large, the AHP exerts cognitive stress on decision makers, which is amplified due to the pairwise comparisons required [49].

2.3.1.3 Principal component analysis

The central idea of PCA is to reduce the dimensionality of a data set consisting of a large number of interrelated variables, while retaining as much as possible the variance present in the data set. This is achieved by transforming to a new set of variables, i.e., the principal components, that are uncorrelated and that are ordered in such way that the first few retain the most of the variation present in all original variables [53]. PCA can be done by eigenvalue decomposition or singular value decomposition of a data covariance matrix, usually after standardising the attribute data. The results of a PCA are usually discussed in terms of component scores and loadings [54].

The procedure was divided in four steps: domain identification, data source acquisition, variable construction and data reduction. PCA was applied to reduce domain-specific data. [55] constructed a water poverty index. PCA was applied to determine sub-indices' weights.

In general, PCA can be used to select a single or a subset of variables to include in the construction of an index that can explain the variation of the overall data set adequately. Thus, it could serve as an aiding tool, enabling the developer to gain a better understanding of the dimensionality in the phenomenon or the structure of the indicators accordingly. PCA can be also used for cases in which the elicitation of weights is not the main goal [10].

For the PCA, certain choices must be made by the decision maker: the number of components to be retained or the rotation method to be used. Hence, subjectivity is introduced to a certain degree. Nonetheless, several criteria or rules exist in the literature for each of the two approaches to facilitate the proper choice [49].

The use of PCA involves the assumptions of having continuous indicators and a linear relationship among them. In the case in which these assumptions do not hold, the use of non-linear PCA is suggested [49].

The nature and philosophy of this approach rely on the statistical properties of the data, which can be seen as both an advantage and a drawback. For instance, the reductionism could be proven to be very useful in some cases in which problems of "double counting" exist. On the other hand, if there is no correlation between the indicators, this technique might even fail to work [49].

Furthermore, the weights that are assigned endogenously by PCA do not necessarily correspond to the actual linkages among the indicators, particularly statistical ones. Therefore, one should be cautious about how to interpret these weights and especially about the extent to which one might use this method, as the truth is that they do not necessarily reflect a sound theoretical framework [49].

Additionally, a general problem with PCA is that it is sensitive to modifications in the basic data. Data revisions and updates, possibly implying additional observations, may change the set of weights that are used to compute the summary indicators. The results are also likely to be sensitive to the presence of outliers, which may introduce a variability in the data, and may suffer from small-sample problems, which are particularly relevant when the focus is on a limited set of companies [10]. However, this issue is addressed with robust variations of PCA. Finally, with the obtained weights being inconsistent over time and space, the comparison might eventually prove to be very difficult [49].

In sum, PCA is a variable reduction technique that can be used when variables are highly correlated; it reduces the number of observed variables to a smaller number of principal components that account for most of the variance in observed variables [54]. These characteristics are the reasons why PCA fits to construct the RI.

There are some critical conditions for conducting PCA. First, a set of variables must be chosen to characterise the reconfigurability. Second, the variables should be constructed separately using PCA and then combined together to compose the RI. Lastly, available and reliable data are indispensable.

A comparison among the aforementioned methods for variables weighting is summarised in table 2.6.

Table 2.6: Common methods for variables weighting

Method name	Type	Example	Benefits	Drawbacks
Equal weighting	Equal weighting	[36]	Simple, replicable and straightforward	No insights into variables relationships; risk of double weighting
AHP	Expert opinion based	[8], [48], [19]	Simple and flexible; available for quantitative and qualitative data	It requires a high number of pairwise comparisons
ANP	Expert opinion based	[18]	It considers the interaction and dependence among variables	It requires a high number of pairwise comparisons
PCA	Statistic based	[54], [56], [55]	Reduces the risk of double weighting, classifying ungrouped variables	Dimensions are unpredictable, and weights may differ from reality

Source: adapted from [50]

2.3.2 Aggregation methods

2.3.2.1 Additive aggregation

Additive aggregation methods employ functions that sum up the normalised values of variables to compose an index. By far, the most widespread additive method is the weighted arithmetic mean [50]. This is the method used in this empirical study.

The continuity characteristic of the weighted arithmetic mean implies that the bound for the index can be precisely defined if the relative measurement error of a set of indicators is already known [50]. This property can be used for sensitivity analysis and uncertainty quantification, both of which are important elements in reconfigurability assessment.

However, the index must be mutually preferentially independent when using linear additive aggregation methods. This means that the contributions of all variables can be added together to yield a total value, implying that no synergy or conflict exists among different variables. In addition, weights used in additive methods are substitution rates instead of importance coefficients because the intrinsic nature of additive methods implies a compensatory logic. Thus, additive methods should not be used when interactions between indicators are substantial [50].

2.3.2.2 Geometric aggregation

Geometric aggregation methods utilise multiplicative instead of additive functions. The most widespread geometric aggregation function is the weighted geometric mean. Unlike additive aggregation methods, geometric mean-based methods only allow compensability between variables within certain limitations. This requirement exists because of the "geometric-arithmetic means inequality", which limits the ability of indicators with very low scores to be fully compensated for by indicators with high scores. Simultaneously, significant marginal effects maybe measured using geometric methods when increasing the values of indicators with relatively low absolute values. On the other side, geometric aggregation methods are not fully non-compensatory techniques, thus they allow for trade-offs among variables, because they are preferentially dependent. Furthermore, with geometric aggregation methods, sensitivity analyses and uncertainty quantification cannot be analysed using measurement errors of indicators [50].

2.3.2.3 Non-compensatory aggregation

Non-compensatory aggregation methods are based on two points of view: the properties of aggregation functions and the perspective of multi-criteria decision making. This approach is based on decision maker preferences and is centred around the fact that a general objective of most indices is to create rankings. Therefore, the core of this method is to construct a ranking algorithm that is more consistent than the linear aggregation rule. The output of this method is a rank rather than a concrete output value for each unit. No compensation is allowed among indicators in the method, and thus, all the weights reflect the relative importance of each indicator instead of a trade-off ratio [50].

Two procedures are used to calculate the index: 1. units are compared pairwise according to the whole set of sub-indicators to construct a ranking matrix; 2. units are ranked in a complete pre-order according to the ranking matrix. There are no restrictions on the type of variables or indicators, which means that both quantitative and qualitative data can be used. Two possible drawbacks of this method are computational limitations associated with the increasing number of units or indicators and the loss of information on the intensity of sustainability [50].

Chapter 3

Empirical study

3.1 Methodology

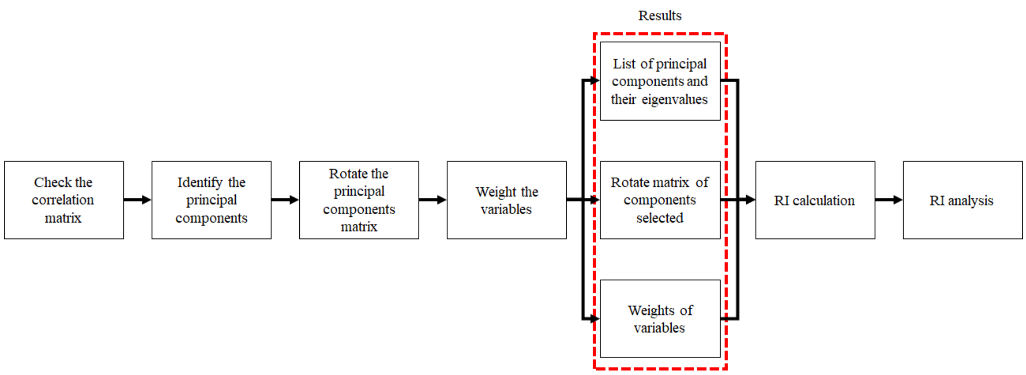
Two aspects must be considered to build an index: the selection of variables and the weight derivation of each variable [12].

The variables were selected from the questionnaire survey developed by [13]. The data were collected by the authors and made available to develop this research.

The weight derivation was carried out through a PCA, which is an exploratory multivariate analysis that assesses the correlation between variables through statistical procedures. To the best of author's knowledge, so far, PCA was not used to develop reconfigurability indices, even though it has been used to develop indices in other domains [10, 12, 49, 54, 56].

The methodology applied to this research is summarised in figure 3.1.

Figure 3.1: Methodology applied to this research



Source: the author.

3.2 Measurement instrument and data collection

3.2.1 Questionnaire survey

The data were collected by [13]. The questionnaire was applied to Portuguese manufacturing companies to identify the implementation level of each core characteristic of reconfigurability and establish their relationship with operational performance measures.

The questionnaire has three sections. The objective of the first section is to characterise respondent companies to understand: the complexity of their products, operations and bill of materials (BOM); the fluctuation on demand, volume, product mix, supply requirements and technical modification of products; the objectives and the frequency of layout modifications.

The second section refers to the core characteristics of reconfigurability. The questions are measured with a 7-point Likert scale, ranging from 1 (strongly disagree) to 7 (strongly agree). The items are described in table 3.1.

Table 3.1: Summary of the variables

Code	Description
mod_{01}	The major equipment in our manufacturing system can be easily added to, or removed from, the shop floor
$modl_{02}$	Our equipment is made of several functional modules that can be easily added/removed
$modl_{03}$	The major equipment in our manufacturing system can be easily reorganised to obtain an adapted configuration to manufacture new products
$intg_{01}$	We can integrate equipment rapidly and precisely by a set of mechanical, informational and control interfaces in our production system
$intg_{02}$	Our equipment is operated/coordinated by an integrated control system, exploited in an open-architecture environment
$intg_{03}$	Our manufacturing system allows an easy integration of new equipment and new technologies
$intg_{04}$	Our equipment and our control system were designed with interfaces that facilitate the integration of new components
$cust_{01}$	The location of our equipment on the shop floor was chosen considering the need to produce an entire product family
$cust_{02}$	Our manufacturing system's capacity and flexibility (hardware and control system) were designed to match the production needs of a product family
$cust_{03}$	Our control system, supported by an open-architecture technology, can be customised to have the exact control functions needed
$conv_{02}$	We can easily stop an equipment operation and reconfigure its functions to manufacture a new product type

Table 3.1: Summary of the variables

Code	Description
$conv_{03}$	We can change quickly from the manufacturing/assembling one product to another, if they are from the same family
$conv_{04}$	Our manufacturing system allows for an easy switch between existing products and can adapt to new/future products
$scal_{02}$	Our manufacturing system can easily respond to unexpected equipment failures
$scal_{03}$	We can easily add equipment, at any stage of the production process, without interrupting operations for long periods
$scal_{04}$	Our throughput can be changed to respond to changes in demand in a relatively short time
$diag_{01}$	Our manufacturing system can automatically detect defective products, diagnose their root causes and reset its parameters to restore the initial situation
$diag_{02}$	Our manufacturing system includes inspection resources that allow the detection of quality defects in real time
$diag_{03}$	Our manufacturing system uses inspection equipment that can be easily reconfigured for use in different stages of the production process
$diag_{04}$	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
$diag_{05}$	Our manufacturing system can automatically identify the source/cause of failures or problems with quality

Source: [13].

The third section presents questions related to operational performance measures of manufacturing systems: quality, delivery, flexibility and costs. The respondents were asked to compare the performance of their companies to the performance of their main competitors. These items were measured using a 7-point Likert scale, ranging from 1 (low end of industry) to 7 (superior). The complete questionnaire can be founded in annex I.

A summary of the variables' descriptive characteristics is shown in table 3.2.

Table 3.2: Summary of the descriptive characteristics of the quantitative variables

Variable	Mean	Standard deviation	Median	Minimun	Maximum
mod_{01}	3,01	1,70	2,00	1,00	6,00
$modl_{02}$	3,16	1,58	3,00	1,00	6,00
$modl_{03}$	3,36	1,66	3,00	1,00	7,00

Table 3.2: Summary of the descriptive characteristics of the quantitative variables

Variable	Mean	Standard deviation	Median	Minimun	Maximum
$intg_{01}$	3,34	1,51	3,00	1,00	7,00
$intg_{02}$	3,27	1,60	3,00	1,00	6,00
$intg_{03}$	4,15	1,43	5,00	1,00	7,00
$intg_{04}$	3,77	1,49	4,00	1,00	7,00
$cust_{01}$	5,14	1,34	5,50	1,00	7,00
$cust_{02}$	5,02	1,38	5,00	1,00	7,00
$cust_{03}$	4,34	1,44	4,50	1,00	7,00
$conv_{02}$	4,53	1,64	5,00	1,00	7,00
$conv_{03}$	5,22	1,49	6,00	1,00	7,00
$conv_{04}$	4,96	1,34	5,00	1,00	7,00
$scal_{02}$	4,36	1,30	5,00	2,00	7,00
$scal_{03}$	4,07	1,49	4,50	1,00	7,00
$scal_{04}$	4,69	1,36	5,00	2,00	7,00
$diag_{01}$	3,47	1,83	3,00	1,00	7,00
$diag_{02}$	4,51	1,55	5,00	1,00	7,00
$diag_{03}$	3,98	1,64	4,00	1,00	7,00
$diag_{04}$	4,16	1,46	4,00	1,00	7,00
$diag_{05}$	3,62	1,66	3,00	1,00	7,00

Source: the author.

3.2.2 Sample and response rate

The questionnaire survey was distributed to 600 Portuguese manufacturing companies and subsidiaries of multinational companies operating in Portugal, that are currently in operation and with an annual turnover of more than €1 million. To build the sample, the companies were selected randomly from an initial list of 11000 organisations, obtained from the Sabi database (`https://www.bvdinfo.com`).

The selection comprises companies from different industrial sectors, grouped in accordance to their size: micro (up to 10 employees), small (from 10 to 49 employees), medium (from 50 to 249 employees) and large companies (more than 250 employees), making a heterogeneous sample. This approach was considered to assure the generalisation of results and a moderate level of external validity [57].

From the distribution, 7 companies did not answer the questionnaire because it was against company's policies and 288 did not give any answer or justification. In total, 305 responses were obtained, but 193 were incomplete. Therefore, there was 112 viable answers from a total of 600 companies, representing a response rate of 18,7%.

The profile of companies surveyed is shown in table 3.3 and 3.4. The profile of respondents is presented in table 3.5.

Table 3.3: Profile of companies surveyed

Size	Frequency	%
Micro	8	7,10
Small	28	25,00
Medium	52	46,40
Large	24	21,40
Total	112	100,00

Source: [13]

Table 3.4: Summary of the ISIC of companies surveyed

ISIC	Description	Frequency	%
29	Manufacture of motor vehicles, trailers and semi-trailers	12	10,71
10	Manufacture of food products	11	9,82
22	Manufacture of rubber and plastics products	11	9,82
24	Manufacture of basic metals	7	6,25
27	Manufacture of electrical equipment	6	5,36
13	Manufacture of textiles	5	4,46
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	5	4,46
25	Manufacture of fabricated metal products, except machinery and equipment	5	4,46
31	Manufacture of furniture	5	4,46
28	Manufacture of machinery and equipment n.e.c.	4	3,57
23	Manufacture of other non-metallic mineral products	3	2,68
14	Manufacture of wearing apparel	2	1,79
15	Manufacture of leather and related products	2	1,79
21	Manufacture of pharmaceuticals, medicinal chemical and botanical products	2	1,79
30	Manufacture of other transport equipment	2	1,79
12	Manufacture of tobacco products	1	0,89
18	Printing and reproduction of recorded media	1	0,89
32	Other manufacturing	28	25,00
Total		112	100,00

Source: [13]

3.2.3 Data validation

The data validation was performed in [4] and [24]. To assess the internal consistency of the scales, the Cronbach's alpha coefficient (α) was calculated. The α value of 0,70 is considered the internal consistency criterion for established scales. A sample of 30 or more responses is statistically enough to calculate α, but the coefficient is more accurate

Table 3.5: Respondents profile

Job title	Frequency	%
General manager	31	27,70
Production manager	17	15,20
Quality manager	11	9,80
Factory manager	9	8,00
Process engineer	8	7,10
Industrial manager	7	6,30
Maintenance manager	3	2,70
Other	26	23,20
Total	112	100,00

Source: [13]

considering large samples [58]. This study sample of 112 responses allowed values of α that varied from $0,73$ to $0,85$, indicating a good level of reliability.

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

The items of the questionnaire were developed based on a literature review and experts' advice. Following the experts' feedback, extra items were eliminated to assure the proper measurement of the core characteristics of reconfigurability. After a pilot test, the questionnaire were slightly modified to make it more understandable. Since all of this involved field-based content validation, the measures can be considered valid, in terms of content [59].

To ensure the construct validity, it is necessary to check its convergent validity and unidimensionality. This is performed through a confirmatory factor analysis (CFA). The initial measurement with all 25 items resulted in an inappropriate fit. Thus, the model was refined using standard CFA procedures. The items with excessive standardised residuals and modification indices were identified and eliminated one at a time. This refinement was interrupted when reaching the acceptable model adjustment limits, without a substantial reduction in the content validity of the constructs. Four items were eliminated from the original 25 items. The fit indices of the refined model met or exceeded the threshold values, with a chi-square model (χ^2) $> 0,05$, an average square root of the approximation error $< 0,08$, an index of comparative adjustment $> 0,90$ and a standard residual mean square root $< 0,08$ [60].

3.3 Principal components analysis

The PCA is a multivariate exploratory analysis that aims to transform a set of correlated variables into a smaller set of independent variables, with the least possible loss of information. The factor loadings of rotated principal components are used to determine the variables' weights. In this way, it is possible to preserve the proportion of the variance of the original data set [49]. A detailed description of the PCA can be seen in [53] and [61]. In this work, the software R was used to conduct the PCA.

The weighting process consists of the following steps:

1) Check the correlation matrix.

2) Identify the principal components.

3) Rotate the principal components matrix.

4) Weight the variables.

The results of the PCA are:

- A list, in decreasing order of variance explained, of the main components and their eigenvalues.

- A rotated matrix (varimax) of the selected components.

- Weights of variables.

3.3.1 Correlation matrix

The calculation of the principal components consists of maximising the variance explained. Therefore, the principal components are represented by the eigenvectors (standardised coefficients) associated with the eigenvalues (variances) of the co-variance matrix. The correlation matrix is used when the data are standardised (mean zero and unit variance). This matrix is adequate to evaluate the linear relationship between two variables in relation to their variance. The variance values can vary in a range from -1 (negative linear relationship) to 1 (positive linear relationship). Values close to zero indicate that there is no linear relationship between the original variables [61].

The correlation matrix obtained is presented in appendix A.

3.3.1.1 Sample adequacy measures

Some tests must be conducted to assure the adequacy of the original variables to the PCA [53]. The tests are:

- *Bartlett's sphericity*. This test verifies the null hypothesis that the correlation matrix is an identity matrix (|R|=1). In other words, this test checks whether the components out of the main diagonal are equal to zero. The probability associated to this test must be lower than the level of significance. The Bartlett's sphericity test returned a p-value of $2,67 \times 10^{-122}$, i.e., approximately zero.

- *Kaiser-Meyer-Olkin (KMO)*. This test examines the adequacy of the original variable by inspecting the correlation coefficients. The results range from 0 to 1: values below $0,50$ are unacceptable; values between $0,50$ and $0,70$ are acceptable; values between $0,70$ and $0,80$ are good; and values above $0,90$ are excellent. The KMO test returned a value of $0,73$, indicating good results. In addition, this test was performed for each variable. The results ranged from $0,53$ to $0,83$, all above the threshold value of 0,50.

- *Multicolinearity*. An evaluation of the relationship between the original variables is required to examine the existence of multicolinearity. To do so, the determinant of the correlation matrix is calculated. Values greater than 1×10^{-5} are acceptable. The result obtained was $2,12 \times 10^{-5}$.

3.3.2 Identification of principal components

The principal components are obtained by a spectral decomposition of the correlation matrix. The results are expressed by the factor loading, which indicate how much each variable is related to each factor, and by the eigenvalues of each principal component. The first component is the linear combination of the most representative variables in terms of variance. The second component represents the second most representative variance and it is not related to the first component. The following components explain lower values of the total variance progressively and are not related to each other.

The selection of the principal components considers 1) the accumulated variance, which means that the principal components should represent at least 60% of the total variance explained, and 2) the eigenvalues that should be greater than or equal to 1, as well as their sum [53, 61].

As can be seen in table 3.6, 21 variables are related to five principal components that explain 66,05% of the total variance explained. The scree plot in figure 3.2 also indicates five principal components.

3.3.3 Rotated matrix

Eventually, the interpretation of the principal components may be difficult due to the similar numerical magnitude of coefficients of different variables. In such case, the purpose of the rotation is to obtain a simpler structure to better understand the contribution of each variable to each principal component. There are two types of rotation: orthogonal, that keeps the uncorrelated factors, and oblique, that allows the correlation of new factors. This work uses the orthogonal rotation (varimax).

Besides, the communality, i.e, the proportion of the variance explained of each variable, should be verified. The results range from 0 to 1; it is zero when the common factors do no explain any variance and it is 1 when they explain all the variance. When the value is lower than $0,50$, it should be considered to increase the size of the sample or eliminate

Table 3.6: Summary of the factors

Factor	Eigenvalue	Variance (%)	Accumulated variance (%)
1	5,30	25,26	25,26
2	2,78	13,23	38,49
3	2,49	11,86	50,35
4	1,99	9,49	59,84
5	1,30	6,21	66,05
6	0,97	4,62	70,67
7	0,87	4,15	74,82
8	0,75	3,58	78,40
9	0,63	2,98	81,38
10	0,54	2,57	83,95
11	0,49	2,33	86,28
12	0,46	2,19	88,47
13	0,43	2,04	90,51
14	0,37	1,75	92,25
15	0,32	1,52	93,77
16	0,31	1,48	95,25
17	0,26	1,24	96,48
18	0,22	1,06	97,53
19	0,20	0,95	98,47
20	0,18	0,84	99,30
21	0,15	0,70	100,00

Source: the author

variables [53]. For samples with 100 to 200 observations, the communalites that vary from $0,40$ to $0,70$ should have at least three factor loadings greater than $0,40$ [62].

The factor loadings and the commnunalities of the variables are shown in table 3.7. The variable $scal_{04}$ presents the lowest value of $0,44$. The variable $cust_{03}$ shows high factor loadings for the principal components of integrability and customisation, $0,58$ and $0,49$, respectively. To satisfy the conditions established by [62], $cust_{03}$ was assigned to the principal component of customisation. Thus, all the principal components have at least three variables with factor loadings greater than $0,40$.

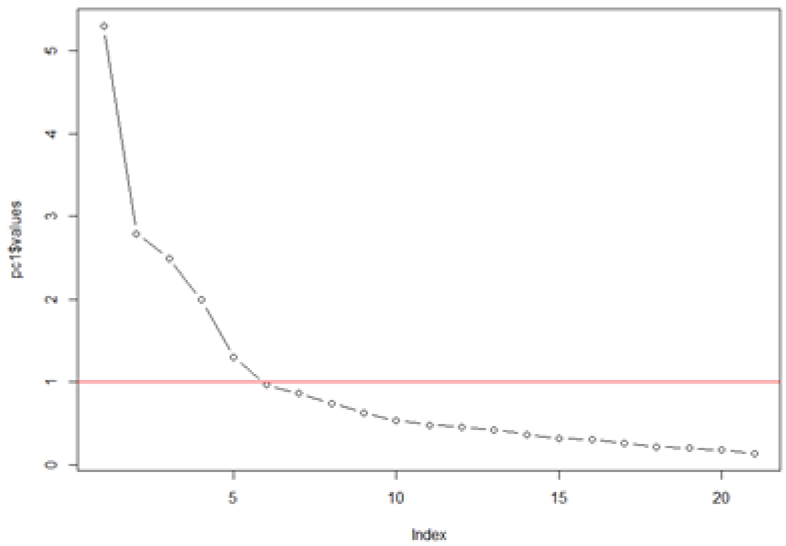
3.3.4 Weighting and aggregation

The weights are defined to correct the overlapping information between correlated variables. This means that the weights are assigned in accordance to their statistical importance in the index construction process [63].

To build the RI, the approach developed by [10] was used to determine the weights of variables and principal components. The principal components represent the core characteristics of reconfigurability.

After the rotation, each variable is weighted according to the proportion of its variance explained. The weights are obtained by squaring and normalising the estimated factor loadings that represent the proportion of the total unit variance of the indicator which is

Figure 3.2: Scree plot



Source: the author

Table 3.7: Factor loadings and communalities after the varimax rotation with Kaizer normalisation

Variables	Modularity	Integrability	Customisation	Adaptability	Diagnosability	Communality
$modl_{01}$	**0,83**	0,07	-0,14	0,04	0,08	0,72
$modl_{02}$	**0,85**	0,08	0,03	0,06	0,15	0,75
$modl_{03}$	**0,74**	0,36	0,00	0,02	-0,02	0,68
$intg_{01}$	0,41	**0,69**	0,13	0,15	-0,02	0,68
$intg_{02}$	0,05	**0,86**	0,03	-0,04	0,17	0,77
$intg_{03}$	0,27	**0,67**	0,05	0,28	0,12	0,62
$intg_{04}$	0,05	**0,80**	0,05	0,16	0,23	0,72
$cust_{01}$	-0,08	0,01	**0,82**	0,12	-0,03	0,70
$cust_{02}$	-0,02	0,19	**0,87**	0,13	0,05	0,82
$cust_{03}$	0,00	0,58	**0,49**	0,01	0,24	0,63
$conv_{02}$	0,17	0,05	0,01	**0,76**	-0,03	0,62
$conv_{03}$	0,14	0,06	0,31	**0,74**	0,03	0,67
$conv_{04}$	0,14	0,07	0,36	**0,71**	-0,08	0,66
$scal_{02}$	-0,33	0,18	-0,11	**0,65**	0,20	0,62
$scal_{03}$	0,11	0,11	-0,08	**0,73**	0,12	0,58
$scal_{04}$	-0,14	0,04	0,07	**0,63**	0,13	0,44
$diag_{01}$	0,02	0,15	0,02	-0,03	**0,75**	0,59
$diag_{02}$	0,02	0,25	0,14	-0,10	**0,75**	0,66
$diag_{03}$	0,15	0,03	0,07	0,13	**0,74**	0,59
$diag_{04}$	0,00	0,07	-0,01	0,16	**0,79**	0,65
$diag_{05}$	0,04	0,09	-0,15	0,16	**0,82**	0,72

Source: the author

explained by the factor [10]. This calculation is represented in equation 3.1, where w_i is the weight of each variable and a_n is the factor loading of the rotated matrix.

$$w_i = \frac{a_n^2}{\sum a_n^2} \tag{3.1}$$

The principal components are calculated based on the weights of variables and the answers of the questionnaire, as represented in equation 3.2, where y_n represents the principal components, w_{ni} represents the weight of each principal component n, i.e, $modl$, $intg$, $cust$, $adap$ and $diag$, and i refers each variable (e.g., $modl_{01}$, $modl_{02}$ and $modl_{03}$) [10, 12, 64]. In equation 3.2, z_{ni} represents the answers of the questionnaire survey.

$$y_n = \sum w_{ni} z_{ni} \tag{3.2}$$

For example, the factor loadings (a_n) of $modl_{01}$, $modl_{02}$ and $modl_{03}$ are $0,83$, $0,85$ and $0,74$, respectively. Consequently, their squared factor loadings (a_n^2) are $0,69$, $0,72$ and $0,55$, which the sum is $1,96$. The weight of each variable can be calculated using equation 3.1. Thus, the weights of $modl_{01}$, $modl_{02}$ and $modl_{03}$ are determined as follows:

$$w_{modl_{01}} = \frac{a^2_{modl_{01}}}{a^2_{modl_{01}} + a^2_{modl_{02}} + a^2_{modl_{03}}} = \frac{0,69}{1,96} = 0,35$$
$$w_{modl_{02}} = \frac{a^2_{modl_{02}}}{a^2_{modl_{01}} + a^2_{modl_{02}} + a^2_{modl_{03}}} = \frac{0,72}{1,96} = 0,37$$
$$w_{modl_{03}} = \frac{a^2_{modl_{03}}}{a^2_{modl_{01}} + a^2_{modl_{02}} + a^2_{modl_{03}}} = \frac{0,55}{1,96} = 0,28$$

Then, the weight of modularity (y_n) is calculated using equation 3.2. In other words, the y_{modl} is calculated multiplying the weight of the variable $modl_{01}$ by the the value of its answer ($z_{modl_{01}}$) plus the weight of the variable $modl_{02}$ by the the value of its answer ($z_{modl_{02}}$) plus the weight of the variable $modl_{03}$ by the the value of its answer ($z_{modl_{03}}$).

$$y_{modl} = 0,35 \times z_{modl_{01}} + 0,37 \times z_{modl_{02}} + 0,28 \times z_{modl_{03}}$$

This procedure was replicated for the 112 respondent companies and the other principal components: y_{intg}, y_{cust}, y_{adap} and y_{diag}. The weights of variables in the principal components are summarised in table 3.8.

The principal components are weighted according to its contribution to the variance explained in the data set (λ). In sum, the weight of adaptability is 0.25, of diagnosability 0.25, of integrability 0.19, of modularity 0.16 and of customisation to 0.15.

These results indicate that adaptability and diagnosability have the highest contribution to the composition of the RI, with 25%. Integrability contributes with 19% and modularity with 16%. The characteristic that contributes the least is customisation, with 15%.

The RI is calculated as described in equation 3.3. Since the index adopts the same scale of the measurement instrument, the results can vary from 1 to 7.

$$RI = \sum y_n \times \lambda_n \tag{3.3}$$

For example, the RI for the first respondent company is represented below.

$$RI_1 = (4,88 \times 0,16) + (1,97 \times 0,19) + (2,00 \times 0,14) + (5,86 \times 0,25) + (5,21 \times 0,25) = 4,24$$

Table 3.8: Summary of variables' and characteristics' weights

Modularity	a_n	a_n^2	w_i
mod_{01}	0,83	0,69	0,35
$modl_{02}$	0,85	0,72	0,37
$modl_{03}$	0,74	0,55	0,28
λ_{modl}	0,16		

Integrability	a_n	a_n^2	w_i
$intg_{01}$	0,69	0,48	0,21
$intg_{02}$	0,86	0,74	0,32
$intg_{03}$	0,67	0,45	0,19
$intg_{04}$	0,80	0,64	0,28
λ_{intg}	0,19		

Customisation	a_n	a_n^2	w_i
$cust_{01}$	0,82	0,67	0,40
$cust_{02}$	0,87	0,76	0,45
$cust_{03}$	0,49	0,24	0,14
λ_{cust}	0,15		

Adaptability	a_n	a_n^2	w_i
$conv_{02}$	0,76	0,58	0,19
$conv_{03}$	0,74	0,55	0,18
$conv_{04}$	0,71	0,50	0,17
$scal_{02}$	0,65	0,42	0,14
$scal_{03}$	0,73	0,53	0,18
$scal_{04}$	0,63	0,40	0,13
λ_{adap}	0,25		

Diagnosability	a_n	a_n^2	w_i
$diag_{01}$	0,75	0,56	0,19
$diag_{02}$	0,75	0,56	0,19
$diag_{03}$	0,74	0,55	0,18
$diag_{04}$	0,79	0,62	0,21
$diag_{05}$	0,82	0,67	0,23
λ_{diag}	0,25		

Source: the author

3.4 Reconfigurability index

From the total of 112 respondent companies, the results ranged from 2,08 to 5,66. 10 companies present the RI in the range $2,00 < \text{RI} \leq 3,00$; 39 companies present the RI in the range $3,00 < \text{RI} \leq 4,00$; 49 companies present the RI in the range $4,00 < \text{RI} \leq 5,00$; and 14 companies present the RI in the range $5,00 < \text{RI} \leq 6,00$. The RI values are classified in accordance to the following scale: none ($1,00 \leq \text{RI} \leq 2,00$), very low ($2,00 < \text{RI} \leq 3,00$), low ($3,00 < \text{RI} \leq 4,00$), moderate ($4,00 < \text{RI} \leq 5,00$), high ($5,00 < \text{RI} \leq 6,00$) and very high ($6,00 < \text{RI} \leq 7,00$). Thus, in general, the majority of Portuguese companies present moderate RI levels. This is shown in table 3.9.

In addition, it is possible to see in table 3.9 that the RI of the majority of companies ranges from low to moderate levels. The same occurs with the implementation levels of integrability and diagnosability. On the other side, most part of companies shows implementation levels of customisation and adaptability ranging from moderate to high. Regarding modularity, the majority presents none to very low levels.

customisation, adaptability and diagnosability. On the other side, most part of companies show implementation levels of integrability ranging from very low to moderate while none to low implementation levels of modularity.

Table 3.9: Number of companies and the implementation level of the core characteristics

	Number of companies					
	None	Very low	Low	Moderate	High	Very high
RI	0	10	39	49	14	0
y_{modl}	34	23	24	22	7	2
y_{intg}	16	22	33	26	14	1
y_{cust}	4	8	10	28	53	9
y_{adap}	1	8	25	34	36	8
y_{diag}	10	19	30	28	24	1

Source: the author

A sample of the results is shown in table 3.10.

Table 3.10: A sample of the results

Company	ISIC	y_{modl}	y_{intg}	y_{cust}	y_{adap}	y_{diag}	RI
89	15	5,63	5,47	5,19	5,92	5,81	5,66
110	24	3,00	1,47	2,61	2,53	1,21	2,08

Source: the author

The company that shows the highest RI (89) belongs to the industrial sector of leather and related products and adopts the make to order (MTO) business production strategy. It has complex products, bill of materials (BOM) and processes. This company faces fluctuations on volume, product mix, supply requirements, technical changes of products and modifications of parts by suppliers weekly, but does not face demand variations frequently.

Adaptability is the core characteristic with the highest level of implementation in this company. This means that the company is able to change between products easily and adjust system's capacity and throughput in a short time to match the market demand. This can only happen if modularity and integrability are implemented in the system as well [2]. As can be observed in table 3.10, both characteristics show high levels of implementation. Customisation, which is the characteristic that synthesises the reconfigurability, on the other side, presents the lowest level of implementation. This indicates that there is room to improve the reconfigurability in this manufacturing system [6, 35].

The company that shows the lowest RI (110) belongs to the industrial sector of basic metals and adopts the engineering to order (ETO) business production strategy. The complexity of company's products, BOM and processes is low. The company faces variations in demand, volume and product mix from week to week. The suppliers need to carry out modifications to the parts frequently, even though the supply requirements do not vary drastically and the products do not suffer a lot of technical modifications.

In this case, modularity has the highest level of implementation. The results seems to indicate that the company is starting the process of implementation of reconfigurability, which begins with the implementation of modularity [2]. On the other hand, diagnosability shows the lowest level of implementation. This may be related to the type of product manufactured. In contrast to the company with the highest RI, which manufactures complex products, such as luggage, handbags and footwear, this company manufactures less complex products, such as tubes and pipes.

3.5 Reconfigurability index analysis by industrial sector

To establish the ranking, shown in table 3.11, companies were grouped according to their ISIC. Industrial sectors with less than two responses were excluded from the ranking.

Table 3.11: Ranking of the industrial sectors surveyed.

ISIC	Description	y_{modl}	y_{intg}	y_{cust}	y_{adap}	y_{diag}	RI
27	Electrical equipment	4,29	4,69	5,25	4,77	4,41	4,65
16	Wood and cork, except furniture; articles of straw and plaiting materials	3,47	4,81	5,71	5,01	4,08	4,58
28	Machinery and equipment	2,89	3,92	5,78	5,08	4,63	4,48
15	Leather and related products	3,82	4,47	5,03	5,08	3,91	4,45
29	Motor vehicles, trailers and semi-trailers	4,04	3,80	4,77	4,70	4,30	4,32
25	Fabricated metal products, except machinery and equipment	3,29	3,30	4,76	5,08	4,13	4,16
32	Other manufacturing	2,97	3,70	5,05	4,89	3,81	4,10
14	Wearing apparel	3,86	3,54	2,22	5,67	4,09	4,08
24	Basic metals	2,96	3,81	5,30	4,26	3,78	3,98
31	Furniture	3,80	3,31	4,36	4,46	3,41	3,85
23	Other non-metallic mineral products	2,43	3,64	4,57	3,57	4,54	3,78
13	Textiles	3,23	3,16	4,50	4,37	3,45	3,74
22	Rubber and plastics products	2,32	3,11	5,16	4,64	3,44	3,73
10	Food products	2,76	3,09	5,02	4,06	3,71	3,70

Table 3.11: Ranking of the industrial sectors surveyed.

ISIC	Description	y_{modl}	y_{intg}	y_{cust}	y_{adap}	y_{diag}	RI
21	Pharmaceuticals, medicinal chemical and botanical products	2,69	2,54	5,93	2,28	5,20	3,64
30	Other transport equipment	1,54	2,33	4,49	5,31	3,79	3,62

The industrial sector ranked first is the manufacture of electrical equipment. This sector includes companies that produce electric motors, generators, transformers and electricity distribution and control apparatus, batteries and accumulators, wiring and wiring devices and domestic appliances. In general, companies surveyed show high complexity, in terms of products, BOM and processes, and high level of fluctuations in demand, volume, product mix, supply requirements and technical modifications of products. In fact, this industrial sector presents the highest level of market fluctuations of the companies surveyed. The majority adopts the MTO business production strategy and product layout.

The complexity of products, BOM and processes, and fluctuations faced by companies surveyed are summarised in table 3.12 and 3.13.

Table 3.12: Summary of the complexity of industrial sectors surveyed

ISIC	Products	BOM	Process
27	Moderate	High	Moderate
16	Very low	Very low	Moderate
28	Very low	Moderate	Low
15	Very high	High	Very high
29	Moderate	Moderate	High
25	Low	Very low	High
32	Moderate	Moderate	High
14	None	Very low	None
24	High	High	High
31	Moderate	Low	Moderate
23	Very low	Moderate	Moderate
13	Moderate	Moderate	High
22	Low	Low	Moderate
10	Moderate	Moderate	High
21	Low	High	Very high
30	Moderate	High	Moderate

As can be observed in table 3.11, the manufacture of electrical equipment shows the highest level of modularity among the industrial sectors surveyed, although moderate. The implementation level of the other core characteristics range from moderate to high. Together with integrability, also implemented at moderate level, modularity allow

Table 3.13: Summary of the fluctuations faced by the industrial sectors surveyed

ISIC	Demand	Volume	Product mix	Supply requirements	Technical modifications	Suppliers modifications
27	High	Moderate	Moderate	High	High	Moderate
16	Low	Low	Moderate	Low	Low	Low
28	Low	Low	Very low	Moderate	Very low	Very low
15	Very low	Low	High	Low	Moderate	Moderate
29	Low	Low	Low	Low	Low	Very low
25	Moderate	Low	High	Moderate	Low	None
32	Low	Low	Low	Low	Low	Very low
14	Moderate	High	High	High	None	None
24	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
31	Moderate	Moderate	High	High	Moderate	Very low
23	Low	Low	Moderate	Low	Low	Very low
13	Low	Low	Low	Low	Moderate	Low
22	Moderate	Moderate	Moderate	Moderate	Low	Very low
10	Moderate	Low	Moderate	Moderate	Low	Very low
21	Low	Very low	Very high	High	None	None
30	Low	Low	Low	High	High	Moderate

a quickly reconfiguration of the manufacturing system, in terms of time and effort [43]. This is essential for this industrial sector that needs to deal with high levels of market variations. Customisation is vital for companies that adopt the MTO strategy [24]. Thus the high level of implementation confirms that companies can cope with the variability. The moderate level of adaptability contributes with the change of production capacity and functionality. Finally, the moderate level of diagnosability means the reduction of ramp up times after each reconfiguration.

The industrial sector ranked last is the manufacture of other transport equipment, which includes the building of ships and boats, and the manufacture of railway locomotives and rolling stock, air and spacecraft and related machinery, military fighting vehicles, motorcycles and bicycles. Companies within this group report products, BOM and processes of high complexity, and moderate levels of variations in demand, volume, product mix, supply requirements and technical modifications of products. Respondent companies declare the adoption of product layout, which changes several times per year.

In the manufacture of other transport equipment, the implementation level of the core characteristics vary significantly, from none to high. The results show that modularity is not implemented. However, it was expected to have higher levels of implementation, because equipment modularity is required when the product is too large or cumbersome or not feasible or not convenient to move through the various processing steps [65]. The same reasoning applies to the integrability, which show low level of implementation. This might indicate that respondent companies do not manufacture large size products such as ships and aircrafts. They may produce other transport equipment such as motorcycles, bicycles or even parts for transport equipment. The implementation level of customisation is moderate. This might imply that respondent companies interpret customisation as the basis to implement reconfigurability. In this case, customisation is the first core characteristic to implement [1]. The implementation level of adaptability is high. This may occur because these companies are able to perform a smooth transition from one product to another, without drastic (hardware) modifications. Lastly, diagnosability is implemented at low level. This is also contrasting, because the safety of transport equipment must be assured. Consequently, processes failures and quality problems must be detected and solved.

The manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials present the highest level of integrability implemented. This sector includes sawmilling and planing of wood, and the manufacture of products of wood, cork, straw and plaiting materials, veneer sheets and wood-based panels, builders' carpentry and joinery and wooden containers. Companies state low complexity of products, BOM and processes, as well as low levels of market variations. The majority adopts the MTO business production strategy and process layout.

This high level of integrability means that these companies are able to integrate new technologies and/or equipment in the existing manufacturing system. Since these companies do not face significant levels of variations, this means that they are prepared to introduce new products anytime. This can be confirmed by the high levels of customisation and adaptability implemented. Even though implemented at a moderate level, diagnosability may not be the most important core characteristic for this sector that does not have complex products, BOM and processes, and does not face frequent market fluctuations. The low level of modularity indicates a stable production process, that does not need to cope with relevant changes in the physical structure of the manufacturing system.

The manufacture of pharmaceuticals, medicinal chemical and botanical products indicates the highest levels of customisation and diagnosability implemented. Companies inform high complex products, BOM and processes, but low levels of fluctuations on demand, volume, product mix, supply requirements and technical modifications of products. The majority adopts the MTO business production strategy and cellular layout. Since companies do not deal with significant levels of market variations, customisation refers to the design around a product family. Diagnosability, on the other hand, means the ability to detect and correct defective products and processes failures. This core characteristic is particularly important for this industrial sector. However, this sector presents very low levels of modularity, integrability and adaptability. In fact, it shows the lowest implementation level of adaptability among the industrial sectors surveyed. This may happen because the implementation of adaptability depends on the implementation of modularity and integrability [2]. Therefore, without these two core characteristics, companies cannot to add or to remove and to disassemble or to reassemble modules, adapt the capacity and functionality of the manufacturing system to better suit new tasks. In other words, without modularity and integrability, it is not possible to achieve adaptability.

The industrial sector of wearing apparel shows the highest level of adaptability but the lowest level of customisation. This combination indicates a production process that postpone, at maximum, the product differentiation. However, products characteristics, e.g. size and colour, can vary. This sector includes the manufacture of wearing apparel, articles of fur, knitted and crocheted apparel, tanning and dressing of leather, manufacture of luggage, handbags, saddlery and harness, dressing and dyeing of fur and footwear. Companies report none complexity and low levels of market fluctuations. The majority adopts the MTS business production strategy and process layout. Modularity and integrability have low levels of implementation. This makes sense since this sector does not face market fluctuations frequently. Diagnosability is implemented at a moderate level.

Lastly, the manufacture of furniture states the lowest level of diagnosability implemented. This is the characteristic that enables the production of good quality products [31].

Modularity and integrability are implemented at low levels. Customisation and adaptability present moderate levels of implementation. Respondent companies inform moderate complexity of products, BOM and processes, as well as moderate levels of fluctuations on demand, volume, product mix, supply requirements and technical modification of products. The most part adopts the MTO business production strategy and process or product layout. Companies concur with an average performance on flexibility to change production volume.

3.6 Reconfigurability index and operational performance

3.6.1 Qualitative analysis

The core characteristics of reconfigurability should be considered to measure the operational performance of RMSs [8]. Thus, the results of y_{modl}, y_{intg}, y_{cust}, y_{adap} and y_{diag} were related to the operational performance, which considers four dimensions: cost, quality, delivery and flexibility [24]. The cost is measured by the unit cost of manufacturing. The quality is measured by the conformance to product specification. The delivery considers on time and fast deliveries. Flexibility is calculated by the flexibility to change the product mix and the production volume.

In table 3.14, companies with none modularity reported an average performance in all dimensions while companies with very low levels of modularity informed a better performance of quality than their main competitors. Companies with low implementation levels reported a better performance than their main competitors in terms of quality and delivery, as well as the companies that inform moderate levels of modularity. These results seem to show that the operational performance improves as the implementation level of modularity increases. Thus, this seems to indicate that the implementation level of modularity has a direct impact on the operational performance.

Table 3.14: Summary of the modularity implementation level and the operational performance

y_{modl}	Implementation level					
	None	Very low	Low	Moderate	High	Very high
Cost	Average	Average	Average	Average	Equivalent	Average
Quality	Average	Better than average	Better than average	Better than average	Average	Average
Delivery	Average	Average	Better than average	Better than average	Average	Better than average
Flexibility	Average	Equivalent	Average	Equivalent	Average	Equivalent

Source: the author

However, companies that present high levels of modularity reported an average performance of quality, delivery and flexibility, and an equivalent performance to their main competitors in terms of cost. Companies that present very high levels of modularity indicated a better performance than average in terms of delivery. On the other side, they presented an average performance of cost and quality and an equivalent performance to their main competitors in terms of flexibility. These companies were expected to report an even better performance than those with moderate levels of modularity. Therefore, this might indicate that there could be an optimal implementation level of modularity that contributes to the improvement of the operational performance.

Regarding integrability, in table 3.15, companies with none integrability implemented indicated a better performance than average in terms of delivery. Companies that has low levels of integrability reported a better performance than average in terms of quality. Companies with moderate levels of integrability presented an average performance in all dimensions. The company that shows very high level of implementation of integrability reported a superior performance than its main competitors in terms of delivery and flexibility. This company also presented a better performance than average in terms of quality.

Table 3.15: Summary of the integrability implementation level and the operational performance

y_{intg}	Implementation level					
	None	Very low	Low	Moderate	High	Very high
Cost	Average	Average	Average	Average	Average	Equivalent
Quality	Average	Average	Better than average	Average	Better than average	Better than average
Delivery	Better than average	Better than average	Average	Average	Better than average	Superior
Flexibility	Equivalent	Average	Equivalent	Average	Average	Superior

In general, the results of integrability seems to indicate that the highest the level of integrability implemented, the better the operational performance. The companies with moderate levels of integrability might be explained by the particularities of their industrial sectors.

As can be observed in table 3.16, the results of adaptability are in accordance to the results of integrability; the operational performance improves as the implementation level of adaptability increases. However, integrability seems to impact more on the performance in terms of quality, delivery and flexibility, while adaptability on cost and quality.

Table 3.16: Summary of adaptability implementation level and the operational performance

y_{adap}	Implementation level					
	None	Very low	Low	Moderate	High	Very high
Cost	Equivalent	Better than average	Average	Average	Average	Better than average
Quality	Equivalent	Average	Average	Better than average	Better than average	Better than average
Delivery	Average	Average	Better than average	Average	Better than average	Average
Flexibility	Average	Average	Equivalent	Average	Average	Average

This makes sense because integrability reduces reconfiguration time and effort, which may impact on products delivery time. The implementation of integrability also contributes to the quickly reconfiguration of manufacturing systems, not only in changing from one product to another, but also in changing the system itself, providing flexibility [66]. Finaly, integrability provides a reliable tool for ramp up, contributing to products quality control [67].

Adaptability, on the other hand, means the rapid adjustment on the capacity and functionality of manufacturing systems to new situations. This assures a high long-term profit-to-cost-ratio and rapid return on investment of RMSs. Minimising costs is important, but the issues of product quality are equally important, because they will affect the operational cost [29].

Referred to customisation, in table 3.17, the companies with none customisation reported a better performance than average in terms of cost and delivery. The companies with very low, low and high levels of customisation informed a better performance than average of delivery. The companies with moderate and very high levels of customisation presented a better performance than average of quality. This was not expected, because companies that do not have customisation implemented showed a better performance in two dimensions, while the companies with high levels of customisation informed a better performance in one dimension.

At first, these results might indicate that the implementation of customisation does not impact on the operational performance. However, companies with none customisation reported a performance in terms of flexibility somewhat lower than their main competitors, while companies that have at least very low levels of customisation implemented informed a performance equivalent to their main competitors or an average performance.

Table 3.17: Summary of customisation implementation level and the operational performance

y_{cust}	Implementation level					
	None	Very low	Low	Moderate	High	Very high
Cost	Better than average	Equivalent	Average	Average	Average	Average
Quality	Average	Average	Average	Better than average	Average	Better than average
Delivery	Better than average	Better than average	Better than average	Average	Better than average	Average
Flexibility	Somewhat lower than	Average	Equivalent	Average	Average	Equivalent

Thus, it seems to exist a relationship between customisation and the operational performance, but more data are required to establish it.

In table 3.18, companies with low levels of diagnosability informed a better performance than average related to quality and delivery, while companies with moderate levels reported a better performance than average in terms of delivery.

Table 3.18: Summary of diagnosability implementation level and the operational performance

y_{diag}	Implementation level					
	None	Very low	Low	Moderate	High	Very high
Cost	Average	Average	Average	Equivalent	Average	Somewhat lower than
Quality	Average	Average	Better than average	Average	Average	Better than average
Delivery	Average	Average	Better than average	Better than average	Average	Superior
Flexibility	Average	Equivalent	Equivalent	Average	Average	Average

In general, only the company with very high levels of diagnosability reported significant improvement of performance. This company presented a better performance than average of quality. This is because diagnosability involves the detection of quality and reliability problems, the diagnoses of root causes of defective products and the correction of operational defects [24]. The company also showed a superior performance of delivery. In contrast, this company reported a performance of cost somewhat lower than its main competitors. This may be related to the additional capital investment required to implement diagnosability [31]. Therefore, it seems that only very high levels of implementation of diagnosability contribute to the improvement of the operational performance, in terms of quality and delivery.

In sum, it can be concluded that:

- The performance in terms of quality and delivery improves as the implementation of modularity increases. However, it seems to exist an optimal implementation level that assures the contribution of modularity to the operational performance.

- The highest the implementation level of integrability and adaptability, the better the performance in delivery and flexibility, and cost and quality, respectively.
- Only very high levels of diagnosability seems to impact on the operational performance, specially on quality and delivery.

3.6.2 Statistical tests

The previous section (3.6.1) discussed the relationship between reconfigurability and the operational performance based on the implementation level of the core characteristics (mean) and the literature. Here, a variance analysis (ANOVA) is performed to test for differences among the variables and to verify whether the aforementioned conclusions can be confirmed statistically.

An ANOVA test is useful to check whether the survey results are significant. The test is performed when it is required to decide whether the sample differences are real, i.e., caused by significant differences in the sample, or casual, i.e., due to sample variability [68].

A one way ANOVA is used to compare two means from two independent (unrelated) groups. The null hypothesis for the test is that the two means are equal. Thus, a significant result implies that the two means are unequal. A one way ANOVA informs that at least two groups are different from each other. However, it does not describe which groups are different. In the later case, an *ad hoc* test is required to inform exactly which groups present a difference in means [68].

The assumptions to conduct an ANOVA test are [69]:

1. *Independent samples*. This means that an observation cannot be influenced by the previous or the next. This assumption ensures that data are collected randomly within the sample space.
2. *Variance homogeneity between groups*. How variance within each group is equal (or at least approximately) within all groups. In this way, each treatment contributes equally to the sum of squares.
3. *Residuals following a normal distribution*. The test assumes that the overall mean of the residuals is equal to zero, i.e., normally distributed. This assumption is not very restrictive depending on the sample size.

The Pearson's chi-squared (χ^2) test was used to assess the independence of variables. This test checks whether observations consisting of measures of two variables are independent of each other. The chi-squared test verifies a null hypothesis stating that the frequency distribution of certain events observed in a sample, which must be mutually exclusive and have a total probability of 1, is consistent with a particular distribution [70]. The Levene test was used to assess the homogeneity. It tests the null hypothesis that the population variances are equal. If the resulting p-value is less than the significance level of 0.05, the differences obtained in sample variances are unlikely to have occurred based on random sampling from a population with equal variance. Therefore, the null hypothesis is rejected, concluding that there is a difference between the variances in the population [71].

Lastly, the Shapiro-Wilk test was applied to check whether the residuals follow a normal distribution. The null hypothesis of this test is that the population is normally distributed. In such case, if the *p*-value is less than 0.05, then the null hypothesis is rejected, meaning that the data tested are not normally distributed [72].

In table 3.19, for modularity, the assumptions of independent samples and variance homogeneity between groups are met. However, three out four operational performance criteria do not satisfy the normal distribution of residuals assumption. In such case, non parametric methods can be used to test whether samples originate from the same distribution. The non parametric equivalent of the one-way ANOVA is the Kruskal-Wallis test, which does not assume a normal distribution of the residuals [73]. Thus, the Kruskal-Wallis test was performed for those items that do not satisfy this assumption.

Table 3.19: ANOVA assumptions: results for modularity

Modularity			
Operational performance	χ^2 *p*-value	Levene *p*-value	Shapiro-Wilk *p*-value
Cost	0.47	0.62	**0.00**
Quality	0.84	0.10	**0.00**
Delivery	0.83	0.94	0.16
Flexibility	0.15	0.22	**0.00**

The ANOVA and Kurskal-Wallis results for modularity and the operational performance are summarised in table 3.20. Delivery is the only criterion that met all ANOVA assumptions. In this case, the ANOVA test for *ad hoc* confidence interval of 95% demonstrates a result of 0.88, which means that there is no significant statistical difference between the core characteristic of modularity and the operational performance of delivery. For cost, quality and flexibility, the Kruskal-Wallis test results present *p*-values greater than 0.05, implying that there are no significant statistical difference as well.

Table 3.20: Modularity implementation level and the operational performance

y_{modl}	Implementation level													
	None		Very low		Low		Moderate		High		Very high		ANOVA	Kruskal
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*p* value	*p* value
Cost	4.26	0.99	4.48	0.99	4.17	1.30	4.73	1.16	3.86	1.07	5.00	0.00	0.33	0.30
Quality	4.76	1.21	5.09	1.06	5.25	0.99	5.09	1.06	4.57	1.13	5.00	0.00	0.52	0.38
Delivery	4.84	1.03	4.83	1.03	5.06	1.03	5.07	1.03	4.93	1.43	5.50	0.00	0.88	0.90
Flexibility	4.12	1.48	3.80	1.55	4.19	1.69	3.95	1.96	4.43	1.69	5.00	1.41	0.87	0.84

Source: the author

The same procedure was replicated for integrability, adaptability, customisation and diagnosability. The appendix B describe these results.

For all cases, only delivery out of the four operational performance criteria meets all the ANOVA assumptions. Thus, the results of the ANOVA test were considered for this criterion. Considering the ANOVA test for *ad hoc* confidence interval of 95%, there is no significant statistical difference between integrability, adaptability, customisation, diagnosability and delivery. However, taking into consideration the ANOVA test for *ad hoc* confidence interval of 90%, there is a significant statistical difference between integrability and delivery. This confirms that the implementation level of integrability influences the operational performance in terms of delivery.

On the other hand, as the ANOVA assumptions are not met, the Kruskal-Wallis test results were considered for cost, quality and flexibility criteria. In such cases, the results show a significant statistical difference (p-value < 0.05) only for integrability and flexibility, and adaptability and cost. This confirms, statistically, the conclusions of the previous section, that state that the highest the level of implementation of integrability, the better the performance on flexibility, and that the highest the level of implementation of adaptability, the better the performance in terms of cost.

In sum, delivery is the only operational performance criterion that satisfy all the assumptions for performing an ANOVA. The test results confirm the influence of integrability on delivery, considering a confidence interval of 90%. The Kruskal-Wallis test was performed for cost, quality and flexibility criteria. The results confirm the influence of integrability on flexibility and of adaptability on cost.

Chapter 4

Conclusion

This work intended to contribute to the reconfigurability level assessment, through the development of a RI, based on the core characteristics of modularity, integrability, customisation, adaptability and diagnosability. This index can be used by manufacturing companies to assess their current level of reconfigurability. Then, managers can use the results to improve the current level of reconfigurability, focusing on weak links and addressing barriers in attaining them

To build the RI, the variables were selected from the measurement instrument proposed by [13]. A PCA with orthogonal rotation (varimax) was used to derive weights and determine the contribution of each core characteristic to the reconfigurability. So far, this method was not used to develop reconfigurability indices, even though it has been used to develop indices in other domains.

In addition, this work presented a ranking of the industrial sectors of companies surveyed and analysed the implementation level of the core characteristics in each, and established a relationship among the core characteristics implementation level and the operational performance.

The main conclusions of this research can be summarised as follows:

- Each core characteristic present different contributions to the reconfigurability. The results show that adaptability and diagnosability contributes with 25% each, integrability with 19%, modularity contributes with 16% and customisation with 15%. This might suggest a cumulative sequence of implementation of the core characteristics to achieve the reconfigurability in manufacturing systems. This sequence could be tested and validated using structural equation modelling.

- In general, the current implementation level of reconfigurability in Portuguese companies is moderate. The reconfigurability can be increased, mainly through the improvement of its core characteristics. Recent studies suggest that the novel technologies promoted by Industry 4.0 may contribute to the implementation of the core characteristics of reconfigurability [2].

- Among the industrial sectors surveyed, the RI varies from 3,64 to 4,65, i.e., from low to moderate levels of reconfigurability implemented. The industrial sector that present the highest RI is the manufacture of electrical equipment, while the manufacture of other transport equipment present the lowest.
- The implementation level of the core characteristics vary among the industrial sectors significantly. For instance, the manufacture of wearing apparel show the highest level of adaptability, but the lowest level of customisation implemented. However, the outcomes seem to indicate that the highest the RI, the highest the levels of fluctuations on demand, volume, product mix, supply requirements and technical modification of products.
- The implementation level of integrability and adaptability seems to influence the operational performance in terms of delivery and flexibility, and cost, respectively. This means that the highest the implementation level, the better the performance. This is confirmed statistically, by an ANOVA test.

This study has some limitations. The third section of the measurement instrument refers to the operational performance of manufacturing systems. However, the relationship among the RI, the core characteristics and the operational performance cannot be confirmed with the data available. Even though the representative response rate (18,7%), the data were collected from companies based in Portugal. Future works should consider to extent it to more companies and/or to other countries. A greater sample might be useful to confirm the findings for the industrial sectors.

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Appendix A

Correlation matrix

Table A.1: Correlation matrix (1/2)

	mod_{01}	$modl_{02}$	$modl_{03}$	$intg_{01}$	$intg_{02}$	$intg_{03}$	$intg_{04}$	$cust_{01}$	$cust_{02}$	$cust_{03}$
$modl_{01}$	1,00									
$modl_{02}$	0,67	1,00								
$modl_{03}$	0,52	0,55	1,00							
$intg_{01}$	0,31	0,38	0.56	1,00						
$intg_{02}$	0,11	0,18	0,29	0,60	1,00					
$intg_{03}$	0,29	0,28	0,39	0,50	0,49	1,00				
$intg_{04}$	0,15	0,15	0,27	0,53	0,67	0,54	1,00			
$cust_{01}$	-0,13	0,01	-0,07	0,16	0,07	0,02	0,12	1,00		
$cust_{02}$	-0,04	0,02	0,07	0,21	0,15	0,26	0,23	0,64	1,00	
$cust_{03}$	0,01	0,15	0,21	0,33	0,48	0,48	0,44	0,26	0,54	1,00
$conv_{02}$	0,07	0,16	0,17	0,20	0,04	0,26	0,24	0,09	0,08	0,01
$conv_{03}$	0,07	0,16	0,11	0,28	0,10	0,27	0,20	0,25	0,32	0,18
$conv_{04}$	0,06	0,08	0,14	0,22	0,09	0,31	0,20	0,28	0,32	0,19
$scal_{02}$	-0,08	-0,10	-0,13	0,07	0,09	0,20	0,22	0,07	0,11	0,17
$scal_{03}$	0,23	0,18	0,09	0,17	0,08	0,30	0,22	0,07	0,11	0,12
$scal_{04}$	-0,09	-0,02	0,03	0,14	0,00	0,16	0,11	0,11	0,20	0,07
$diag_{01}$	0,09	0,15	0,09	0,07	0,23	0,10	0,35	0,00	0,06	0,29
$diag_{02}$	0,07	0,12	0,11	0,20	0,32	0,23	0,34	0,01	0,19	0,30
$diag_{03}$	0,12	0,15	0,14	0,16	0,18	0,25	0,15	-0,05	0,13	0,24
$diag_{04}$	0,02	0,18	-0,02	0,10	0,22	0,15	0,33	0,05	0,01	0,19
$diag_{05}$	0,13	0,12	0,05	0,06	0,24	0,27	0,25	-0,06	-0,06	0,15

Source: the author

Table A.2: Correlation matrix (2/2)

	$conv_{02}$	$conv_{03}$	$conv_{04}$	$scal_{02}$	$scal_{03}$	$scal_{04}$	$diag_{01}$	$diag_{02}$	$diag_{03}$	$diag_{04}$	$diag_{05}$
$modl_{01}$											
$modl_{02}$											
$modl_{03}$											
$intg_{01}$											
$intg_{02}$											
$intg_{03}$											
$intg_{04}$											
$cust_{01}$											
$cust_{02}$											
$cust_{03}$											
$conv_{02}$	1,00										
$conv_{03}$	0,57	1,00									
$conv_{04}$	0,57	0,69	1,00								
$scal_{02}$	0,29	0,36	0,19	1,00							
$scal_{03}$	0,40	0,38	0,46	0,56	1,00						
$scal_{04}$	0,37	0,34	0,30	0,48	0,36	1,00					
$diag_{01}$	-0,02	-0,01	0,00	0,15	0,18	0,08	1,00				
$diag_{02}$	-0,09	0,04	-0,02	0,12	0,00	0,11	0,55	1,00			
$diag_{03}$	0,12	0,13	0,09	0,12	0,16	0,22	0,36	0,55	1,00		
$diag_{04}$	0,16	0,17	0,06	0,21	0,16	0,15	0,52	0,45	0,52	1,00	
$diag_{05}$	0,13	0,16	0,02	0,28	0,20	0,08	0,54	0,51	0,57	0,64	1,00

Source: the author

Appendix

B

Statistical tests

The following tables describe the results of the statistical test to test the assumptions to conduct an ANOVA. In the tables, the standard deviation (SD) columns with NA (not applicable) indicates that there is only one observation.

Table B.1: ANOVA assumptions: results for integrability

Integrability			
Operational performance	χ^2 *p* value	Levene *p* value	Shapiro-Wilk *p* value
Cost	0.99	0.96	**0.00**
Quality	0.21	0.34	**0.00**
Delivery	0.17	0.90	0.15
Flexibility	**0.00**	0.11	**0.02**

Table B.2: Integrability implementation level and the operational performance

y_{intg}	Implementation level													
	None		Very low		Low		Moderate		High		Very high		ANOVA	Kruskal
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*p* value	*p* value
Cost	4.44	1.26	4.27	1.12	4.33	1.14	4.38	1.06	4.50	1.09	4.00	NA	0.99	0.99
Quality	4.88	1.09	4.77	1.02	5.09	1.20	5.00	0.94	5.14	1.23	6.00	NA	0.79	0.70
Delivery	5.28	0.98	5.14	0.95	4.73	1.13	4.69	1.00	5.11	1.00	7.00	NA	0.09	0.14
Flexibility	3.69	1.94	4.73	1.62	3.45	1.36	4.35	1.54	4.25	1.58	6.50	NA	0.03	**0.02**

Source: the author

Table B.3: ANOVA assumptions: results for adaptability

Adaptability			
Operational performance	χ^2 *p* value	Levene *p* value	Shapiro-Wilk *p* value
Cost	0.20	0.68	**0.00**
Quality	0.65	0.30	**0.00**
Delivery	0.88	0.16	0.06
Flexibility	0.35	**0.01**	**0.00**

Table B.4: Adaptability implementation level and the operational performance

y_{adap}	Implementation level													
	None		Very low		Low		Moderate		High		Very high		ANOVA	Kruskal
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*p* value	*p* value
Cost	4.00	NA	5.13	1.13	4.28	0.84	4.03	1.06	4.36	1.15	5.38	1.19	0.01	**0.03**
Quality	4.00	NA	5.00	1.07	4.64	0.86	5.09	1.11	5.06	1.17	5.00	1.07	0.35	0.34
Delivery	5.00	NA	4.63	1.16	5.08	0.85	4.90	1.06	5.01	1.09	4.75	1.49	0.90	0.90
Flexibility	4.50	NA	4.56	0.73	3.66	1.44	4.10	1.68	4.19	1.73	4.13	2.30	0.77	0.78

Source: the author

Table B.5: ANOVA assumptions: results for customisation

Customisation			
Operational performance	χ^2 *p* value	Levene *p* value	Shapiro-Wilk *p* value
Cost	0.68	0.87	**0.00**
Quality	0.37	0.40	**0.00**
Delivery	0.83	0.96	0.11
Flexibility	0.65	0.96	**0.01**

Table B.6: Customisation implementation level and the operational performance

y_{cust}	Implementation level													
	None		Very low		Low		Moderate		High		Very high		ANOVA	Kruskal
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*p* value	*p* value
Cost	5.50	1.29	3.88	0.99	4.40	0.84	4.29	1.18	4.30	1.08	4.89	1.05	0.15	0.14
Quality	5.00	1.54	4.50	0.93	5.00	0.82	5.11	1.13	4.96	1.11	5.22	1.30	0.80	0.75
Delivery	5.38	1.11	5.13	1.27	5.35	0.88	4.70	1.05	5.01	1.03	4.56	1.13	0.38	0.48
Flexibility	2.88	2.17	4.63	1.53	3.95	1.82	4.21	1.57	3.89	1.54	4.06	1.64	0.64	0.73

Source: the author

Table B.7: ANOVA assumptions: results for diagnosability

Diagnosability			
Operational performance	χ^2 *p* value	Levene *p* value	Shapiro-Wilk *p* value
Cost	0.47	0.62	**0.00**
Quality	0.84	0.10	**0.00**
Delivery	0.83	0.94	0.16
Flexibility	0.15	0.22	**0.00**

Table B.8: Diagnosability implementation level and the operational performance

y_{diag}	Implementation level													
	None		Very low		Low		Moderate		High		Very high		ANOVA	Kruskal
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	p value	p value
Cost	4.30	0.82	4.63	1.01	4.50	1.17	4.00	1.05	4.50	1.22	3.00	NA	0.26	0.21
Quality	4.50	1.18	4.95	1.08	5.23	1.04	5.00	1.12	4.88	1.08	6.00	NA	0.46	0.40
Delivery	4.75	1.16	4.71	1.07	5.07	1.06	5.09	1.03	4.83	1.02	6.50	NA	0.46	0.36
Flexibility	4.25	2.00	3.92	1.71	3.85	1.38	4.29	1.71	4.10	1.71	5.00	NA	0.90	0.85

Source: the author

Annex I

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 14 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 refer always 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

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 starts 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

[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 functionalities of this product.

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 process	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

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
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 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

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 average	Superior
Unit cost of manufacturing	1	2	3	4	5	6	7
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 change product mix	1	2	3	4	5	6	7
Flexibility to change volume	1	2	3	4	5	6	7