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Understanding reconfigurability of manufacturing systems: An empirical analysis

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ABSTRACT

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

1. Introduction

In the 1980s, the concept of *flexible manufacturing systems* was introduced in order to respond to the need for mass customization and greater responsiveness to the changes in products, production and market, driven by aggressive economic competition on a global scale, more demanding customers and the rapid pace of change in process technology [1,2]. A cost-effective response to market changes, which can be created by part family focus and customized flexibility, requires a manufacturing approach that is able to react to changes quickly and efficiently and that enables the operation of simultaneous tools [3]. By the end of the 1990s, the concept of a *reconfigurable manufacturing system* had emerged as an attempt to achieve responsive systems, capable of producing high quality products at low costs, by providing an adjustable structure, changeable functionalities, scalable capacity and flexibility [3–5]. Reconfigurable Manufacturing Systems (RMS) are designed at the outset for a rapid change in structure to adjust the production capacity and functionality quickly within a part family in response to sudden changes in manufacturing requirements [3]. An RMS is also designed to produce a particular family of products and to cope with situations where productivity and responsiveness are of vital importance. Its main components for machining are CNC machines and Reconfigurable Machine Tools (RMT), which are controlled, coordinated and operated in an open-architecture environment [3].

In sum, at an operational/tactical level, reconfigurability can be seen as the ability to rearrange manufacturing elements in order to adjust to new environmental and technological changes [6] and, at a tactical/strategic level, as an engineering characteristic that deals with the design of machines and systems for customized products in a cost effective market [7].

RMS assume a relevant role in manufacturing systems by providing a way to achieve a rapid and adaptive response to change, which is a key enabler of competitiveness [8]. Nowadays, disruptive technologies, such as cloud computing, Internet of Things (IoT), big data and analytics, augmented reality and additive manufacturing are permeating the manufacturing industry and making it smart and capable of addressing current challenges, such as increasingly customized requirements, improved quality, and reduced time to market [9]. Thus, it can be expected that these novel technologies, preconized by the concept of industry 4.0, might significantly contribute to increase the reconfigurability of manufacturing systems.

Several authors state that an ideal RMS should possess core characteristics to increase the speed of its responsiveness when faced with unpredicted events, such as sudden market changes or machine failures [4,7,10,11]. Nevertheless, there is no consensus regarding the number and types of RMS core characteristics yet. In fact, in [3] five RMS characteristics are presented: modularity, integrability, customization, convertibility and diagnosability. Later, in [12] scalability is introduced as a new RMS characteristic. These six characteristics have been considered as the core characteristics of RMS by most authors [5,13–15].

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However, other different characteristics have been, to a lesser extent, put forward such as mobility, universality, compatibility, flexibility and self-abilities (e.g. self-adaptation) [4]. Therefore, it is possible to consider that RMS must possess several distinct characteristics and that the sum of these characteristics determines the ease and the cost of reconfiguring manufacturing systems.

Several authors argue that RMS possess the advantages of both dedicated lines and flexible systems [5,10,16,17]. Furthermore, Mehrabi [18] present the challenges expected to be faced by manufacturing systems and how RMS will have a core role in responding to these challenges. Thus, it is expected that RMS will attract the interest of a large number of companies [11]. Additionally, as the need for more reconfigurable systems increases, knowing the various characteristics of RMS becomes of foremost importance in the interest of the manufacturer to be prepared and equipped to evaluate and decide the extent of reconfigurability for their production systems [7]. Therefore, a better understanding of RMS and their core characteristics is required to help companies to assess their present level of reconfigurability and to provide guidelines to improve it in either existing or new manufacturing systems.

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

The remainder of this paper is organized as follows: Section 2 provides a literature review on the topic of RMS. Section 3 presents the research methodology and the analysis of reliability and validity of the questionnaire. The data collected are analysed and discussed in section 4. Finally, section 5 presents the conclusions, the limitations of this research and suggestions for future studies.

2. Literature review

The current production scenario, characterized by aggressive competition and rapid evolution in process technologies, requires more flexible, robust, reconfigurable and easily upgradable systems that rapidly adjust their production capacity and functionality, integrate new technologies and launch new product models quickly, supporting an agile response to the changing conditions through their dynamic reconfiguration on the fly (i.e., without stopping, reprogramming, restarting the processes or the other system components) [8,18,19]. In order to stay competitive, manufacturing companies must remain highly sensitive to market (fluctuations) and be able to react quickly to market changes by introducing products that meet customer needs in a timely manner and by producing high quality products at low costs [5,11].

A cost effective approach that encompasses these capabilities is RMS, whose capacity and functionality can be modified exactly when needed [10]. RMS are cost effective because they boost productivity and increase the lifetime of a manufacturing system [5]. They are created at the design stage to be capable of making rapid changes in the structure and hardware/software components to adjust the production capacity and functionality quickly in response to sudden changes in irregular market demand [11]. RMS may be able to overcome both Dedicated Manufacturing Systems (DMS) and Flexible Manufacturing Systems (FMS), by providing a significant reduction of costs and time in the launching of new products and in the integration of new manufacturing processes into existing systems [20].

RMS are an attempt to achieve changeable functionality and scalable capacity, by proposing a manufacturing environment where components, machines, cells or material handling units can be added, removed, modified or interchanged as needed to respond quickly to changing requirements [15]. However, the objectives of RMS go beyond the rearrangement of its components. This type of system allows, inclusively, the reduction of the time required for designing new systems and for reconfiguring existing ones, and the rapid modification and integration of new technology or functions into existing systems. Additionally, RMS may contribute to the reduction of product costs, continuous improvement in product quality and increased flexibility and responsiveness [5,18].

Koren [3] proposed the concept of RMS and established that it must be designed using hardware and software modules that can be integrated quickly and reliably, thus facilitating the reconfiguration process. RMS should also use modular equipment to achieve the system functionality required for the production of a part family through scalability and reconfiguration as needed, when needed, to meet market demands [4,13]. To achieve these design goals, RMS must have some core characteristics.

When this concept emerged, five core characteristics were described and considered essential for RMS, namely modularity, integrability, convertibility, diagnosability and customization [3]. Several authors supported and enhanced these characteristics [6,18,20,21]. Although [3] and [18] mentioned the increasing need for an adjustable structure for manufacturing systems, enabled by rapid changes in the system production capacity, scalability was only later introduced as another core characteristic of RMS [4]. The six core characteristics of RMS considered by the majority of authors are described hereafter.

Modularity means that all its major components are modular (e.g. structural elements, axes, controls, software, hardware and tooling) and the compartmentalization of operational functions into units can be manipulated between alternate production schemes for optimal configuration arrangement [3,10,13]. *Integrability* is related to the ability to readily integrate these modular components, by a set of mechanical, informational and control interfaces that facilitate integration and communication, which also allow the future integration of new technologies [10,18]. *Customization* has two main aspects: customized control, obtained through the integration of control modules with the aid of open-architecture technology, which provides the exact control functions needed; and customized flexibility, where machines are built around family parts and that provides only the flexibility needed to produce those specific parts [3,22]. *Convertibility* is the characteristic that allows the system, in an operating mode, to change quickly between existing products or different batches, by changing tools, part-programs and fixtures, possibly requiring manual adjustment, allowing the system to adapt for future products. It also concerns the ability to transform the existing functionalities of machines to suit new production requirements easily [3,18]. *Scalability* concerns the ability to modify production capacity incrementally by adding/removing resources or changing system components, rapidly and economically [4,10,23]. *Diagnosability* refers to the detection of unacceptable quality of parts and reliability problems, which are critical factors regarding the reduction of ramp-up time in RMS. As production systems become more reconfigurable and are modified more frequently, the ability to read the current state of a system to detect and diagnose the root cause of output product defects automatically and then quickly correct operational defects, becomes essential in order to rapidly tune the newly reconfigured system [3,10,18].

As mentioned previously, although RMS have been discussed over the last decades, there are only a few empirical studies concerning how this concept could be transferred and implemented by industry. Some efforts have been made to quantify some of the core characteristics of

Table 1
Reconfigurability items used.

Items	References
Modularity	[3,10,12,18,21,29]
The major equipment in our manufacturing system can be easily added to, or removed from, the shop floor	
Our equipment is made of several functional modules that can be easily added/removed	
The major equipment in our manufacturing system can be easily reorganized to obtain an adapted configuration to manufacture new products	
Our material handling system (between workstations) allows an easy rearrangement of the process flow, by adding/ignoring operations, according to the product to be manufactured	
Our manufacturing system is composed by hardware and software modules that can be integrated quickly and reliably	
Integrability	[4,10,12,18,26]
We can integrate equipment rapidly and precisely by a set of mechanical, informational and control interfaces in our production system	
Our equipment is operated/coordinated by an integrated control system, exploited in an open-architecture environment	
Our manufacturing system allows an easy integration of new equipment and new technologies	
Our equipment and our control system were designed with interfaces that facilitate the integration of new components	
Customization	[3,12,18,26]
The location of our equipment on the shop floor was chosen considering the need to produce an entire product family	
Our manufacturing system's capacity and flexibility (hardware and control system) were designed to match the production needs of a product family	
Our control system, supported by an open-architecture technology, can be customized to have the exact control functions needed	
Convertibility	[3,4,10,18,25,26]
The capacities of our manufacturing system and of our equipment can be easily transformed to respond to changes in production requirements	
We can easily stop an equipment operation and reconfigure its functions to manufacture a new product type	
We can change quickly from the manufacturing/assembling one product to another, if they are from the same family	
Our manufacturing system allows for an easy switch between existing products and can adapt to new/future products	
Scalability	[4,10,12,33]
Our production capacity can be changed by adding/removing equipment or by changing the system's components	
Our manufacturing system can easily respond to unexpected equipment failures	
We can easily add equipment, at any stage of the production process, without interrupting operations for long periods	
Our throughput can be changed to respond to changes in demand in a relatively short time	
Diagnosability	[3,10,12,18,24]
Our manufacturing system can automatically detect defective products, diagnose their root causes and reset its parameters to restore the initial situation	
Our manufacturing system includes inspection resources that allow the detection of quality defects in real time	
Our manufacturing system uses inspection equipment that can be easily reconfigured for use in different stages of the production process	
In a start-up phase, we can adjust the manufacturing system parameters, thus reducing the ramp-up time, because we have mechanisms that allow a quick diagnosis of problems with quality	
Our manufacturing system can automatically identify the source/cause of failures or problems with quality	

RMS. A study on diagnosability measures throughout the total life cycle and integrating the system's design and manufacturing process, was conducted by [24], and resulted in a diagnosability index to evaluate and control quality defects of products and equipment failures. Maier-Sperredelozzi [25] proposed metrics to evaluate the convertibility of production systems and of machines, based on assessments of convertibility itself, which were applied to an industrial case that compared the convertibility of two different configurations of a system. Gumasta [7] developed a reconfigurability index, considering modularity, scalability, convertibility and diagnosability, conducting an illustrative example to enlighten the developed methodology. Farid [26] considered integrability, convertibility and customization to discuss how these characteristics fit the requirements for reconfigurability measures in manufacturing systems. Wang [11] developed an evaluation index system for RMS reconfiguration schemes, which was initiated based on the six key RMS characteristics. Regarding the questionnaire-based methodology, research has been restricted to the identification of trends and perspectives for RMS [27] and to the identification of the key requirements for the design of changeable manufacturing and assembly systems [28]. Despite these attempts to assess reconfigurability through its core characteristics, none has empirically tested or validated the existence of those core characteristics. For this reason, this paper reports an empirical research, more specifically, a questionnaire survey, that was conducted with Portuguese manufacturing companies to identify the core characteristics of RMS.

3. Research methodology

3.1. Survey development and data collection

The aim of the proposed survey is to analyse the understanding of reconfigurability and its core characteristics on manufacturing systems empirically. Considering the competitive production environment, manufacturing companies should be able to react rapidly and cost-effectively to unpredictable changes that occur at an increasing pace, such as large fluctuations in product demand and in product mix [29]. The reconfiguration process requires major changes in complete cells and systems, as well as in the software used for planning and controlling processes and production. All this adds to the ever growing complexity of products, processes, manufacturing systems and enterprises [4]. Consequently, these changes can affect the performance of the current layout configuration, triggering the need to rearrange resources for the next production period [30]. Taking this into account, the first part of the survey (appendix, section A) was developed to characterize respondent companies, seeking to understand: the level of complexity of their products, operations and Bill of Materials (BOM); the extent of the variability in demand or product mix and the objectives and frequency of layout rearrangement.

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

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

Following the experts', the Scientific Committee's and Dillman's [31] recommendations, companies were contacted by phone to identify the respondents and to introduce the objectives of the study. An electronic survey (e-survey) was developed, but the access link to the questionnaire was e-mailed exclusively to the target respondents. The main advantages of this data collection method are the lowest relative cost and the ease of securing information. However, the e-survey usually has lower response rates than other survey methodologies [32]. To ensure a satisfactory response rate a reminder e-mail was sent to urge non-respondents to complete the survey if they had not done so already two weeks after the first contact. Then, two weeks after that reminder, a final appeal was sent to non-respondents. A summary of the survey results was promised to the respondents, evaluating the extent of reconfigurability in their companies.

3.2. Response rate and characterization of the respondents

The questionnaire targeted 600 Portuguese manufacturing companies and subsidiaries of multinational companies operating in Portugal. The 600 manufacturing companies were randomly selected from an initial list of 11,000 organizations to construct the sample, which was mainly obtained from the Sabi database (https://www.bvdinfo.com). The companies selected are currently in operation and have an annual turnover of more than 1 million euros. The selection covers manufacturing companies from different industrial manufacturing sectors and are clustered according to their sizes, namely micro- (< 10 employees), small- (10 to 49 employees), medium-sized (50 to 249 employees) and large companies (> 250 employees), yielding a heterogeneous sample [34]. This approach was used to ensure a moderate level of external validity and to contribute to the generalization of the results [32]. The preferred target respondents were the managers with direct involvement in operational and strategic decision-making and knowledge of production processes and strategies. From the survey distribution, 7 companies did not respond to the questionnaire, because it was against the companies' policies and 288 did not give any response or justification. In total, 305 responses were received, of which 193 were incomplete, i.e., the respondent did not answer all the questions.

Table 2
Sample characteristics.

Characteristic	Frequency	%
Number of employees		
< 10	8	7.0
10 to 49	28	25.0
50 to 249	52	46.4
> 250	24	21.4
Total	112	100.0
Respondent's job title		
General manager	31	27.7
Production manager	17	15.2
Quality manager	11	9.8
Factory manager	9	8.0
Process engineer	8	7.1
Industrial manager	7	6.3
Maintenance manager	3	2.7
Other	26	23.2
Total	112	100.0

Table 3
Measures of complexity and flexibility in the companies surveyed.

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

Consequently, there were 112 usable responses from a population of 600 companies, representing an overall response rate of 18.7%. Table 2 summarizes detailed data about the composition of the sample and respondents.

3.3. Characterization of production systems and layouts

The respondent companies were also asked about their production policies and the type of production layout. The most commonly adopted policies are make-to-order (MTO-51.8%), engineer-to-order (ETO-19.6%), assembly-to-order (ATO-17.0%) and make-to-stock (MTS-11.6%). The majority of the companies surveyed seems to have a high level of customization, since the most applied production policies implies that assembly and manufacturing operations, or even the products' design, only start after receiving firm orders from the customers. Regarding the complexity, the results show complex operations, BOM and products. To understand the characteristics of the supply chain that companies face, they were asked about several criteria (Table 3). The majority of the respondents reported that changes to product mix,

Table 4
Frequency and criteria considered when changing layout configuration.

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

Table 5
Scales' validity and reliability.

Scale	Nº of items	Cronbach's α	Factor loading	Mean	SD
Customization	**3**	**0.731**		**4.83**	**1.12**
Our manufacturing system's capacity and flexibility (hardware and control system) were designed to match the production needs of a product family			0.845	5.02	1.38
The location of our equipment on the shop floor was chosen considering the need to produce an entire product family			0.827	5.14	1.34
Our control system, supported by an open-architecture technology, can be customized to have the exact control functions needed			0.740	4.34	1.44
Adaptability	**7**	**0.818**		**4.59**	**0.99**
We can easily stop an equipment operation and reconfigure its functions to manufacture a new product type			0.789	4.53	1.64
We can easily add equipment, at any stage of the production process, without interrupting operations for long periods			0.729	4.07	1.49
We can change quickly from the manufacturing/assembling of one product to another, if they are from the same family			0.728	5.22	1.46
Our manufacturing system allows for an easy switch between existing products and can adapt to new/future products			0.714	4.96	1.34
Our manufacturing system can easily respond to unexpected equipment failures			0.628	4.36	1.30
Our throughput can be changed to respond to changes in demand in a relatively short time			0.599	4.69	1.36
The capacities of our manufacturing system and of our equipment can be easily transformed to respond to changes in production requirements			0.507	4.31	1.43
Diagnosability	**5**	**0.847**		**3.98**	**1.27**
Our manufacturing system can automatically identify the source/cause of failures or problems with quality			0.812	3.63	1.66
In a start-up phase, we can adjust the manufacturing system parameters, thus reducing the ramp-up time, because we have mechanisms that allow the quick diagnosis of quality problems			0.782	4.16	1.46
Our manufacturing system includes inspection resources that allow the detection of quality defects in real time			0.760	4.51	1.55
Our manufacturing system uses inspection equipment that can be easily reconfigured for use at different stages of the production process			0.746	3.98	1.64
Our manufacturing system can automatically detect defective products, diagnose their root causes, and reset its parameters to restore the initial situation			0.735	3.47	1.83
Integrability	**4**	**0.833**		**3.63**	**1.23**
Our equipment is operated/coordinated by an integrated control system, exploited in an open-architecture environment			0.856	3.27	1.60
Our equipment and our control system were designed with interfaces that facilitate the integration of new components			0.796	3.77	1.49
We can integrate equipment rapidly and precisely by a set of mechanical, informational and control interfaces in our production system			0.669	3.34	1.51
Our manufacturing system allows for an easy integration of new equipment and new technologies			0.665	4.15	1.43
Modularity	**3**	**0.805**		**3.51**	**1.20**
Our equipment is made of several functional modules that can be easily added/removed			0.845	3.16	1.58
The major equipment in our manufacturing system can be easily added to, or removed from, the shop floor			0.827	3.01	1.70
The major equipment in our manufacturing system can be easily reorganized to obtain an adapted configuration to manufacture new products			0.740	3.36	1.67

variations in supply requirements and demand fluctuations occur on a weekly basis, while volume fluctuations, technical modifications of products and modifications to parts/components by suppliers are less frequent. These results highlight the need for a highly responsive system, able to respond quickly to sudden market changes.

The most common layout configuration is the process layout (55.4%), followed by product layout (25.9%) and cellular layout (18.8%). Referring to the frequency of layout rearrangement (Table 4), respondents reported that production layout is not modified frequently, i.e. the system's structure is predominantly fixed. However, when a layout change occurs, the impact on lead time and throughput are more important than the impact on material handling costs and work in progress levels.

3.4. Reliability and validity analysis

The goodness of measures is evaluated according to reliability and validity. The lack of reliability introduces a random error while the lack of validity introduces a systematic error [35]. Reliability refers to the stability and the consistency in the measurement score and indicates dependability, predictability and accuracy, because it refers to the extent to which a measuring procedure achieves the same results in repeated trials [32]. In this research, the internal consistency method was used to assess the reliability. In order to assess the internal consistency of the scales, Cronbach's coefficient alpha (α) was calculated. It is expressed in terms of the average inter-item correlation ($\overline{\rho}$) among the n measurement items in the instrument under consideration [36], as follows:

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

The alpha value of 0.7 is often considered the criterion for internal consistency for established scales, but the value of 0.6 is acceptable in the case of newly developed measures. An α ≥ 0.8 indicates that the measure is very reliable [37]. Although the cut-off levels for exploratory research are less stringent, in this study, an $\alpha \geq 0.6$ was considered as the criterion, due to its exploratory nature [38].

Regarding the internal consistency, the sample size is an important factor, because significance tests were developed for large samples. A sample size of 30 or more is statistically sufficient to calculate the alpha, but it is possible to have more confidence in the accuracy considering large samples [37]. This study sample of 112 respondents permitted alpha values that ranged from 0.731 to 0.841, which indicates a good level of reliability. Validity concerns the extent to which the instrument captures what it is intended to capture. The content validity refers to the degree to which the meaning of a set of items represents the domain of the concept under investigation, while the construct validity refers to the degree to which the scores obtained using a set of items behave as expected. The items of this survey questionnaire were constructed based on a literature review and experts' consultancy. Considering their feedback, extra items were eliminated, assuring that the core characteristics of reconfigurability were properly measured. After a pilot study a few modifications were made to the questionnaire, making it more understandable. Since all this involved field-based content validation, the measures could be generally considered to have content validity [39].

To assure the construct validity, the first property to check is the construct's unidimensionality. To be considered unidimensional, an empirical indicator must be significantly associated with an underlying latent variable and with only one latent variable. Evaluating unidimensionality can be performed numerically with an Exploratory Factor Analysis (EFA) [32]. An EFA by principal components with an orthogonal rotation (varimax) was conducted for the reconfigurability characteristics. The factor analysis had five eigenvalues greater than one, suggesting the presence of five factors, and a total variance explained of 65%. The rotated solution was examined to determine if the items in a scale that loaded on more than one factor were meaningful or unwanted nuisance factors. Those which were a nuisance or which represented more than one domain were eliminated. Also, the factor loading of items that did not exceed the generally recommended minimum value of 0.4 were discarded [38]. Then, Cronbach's alpha was recalculated and the remaining items were refactored. Table 5 demonstrates the final version of the scales.

4. Data analysis and findings

4.1. Exploratory factor analysis

The factor analysis (Table 5) shows that the companies surveyed distinguish five core factors. The items concerning convertibility and scalability have loaded on the same factor, meaning that these characteristics are interpreted as a single one. For a manufacturing system to be reconfigurable, it must be capable of modifying functionality and/or capacity, in a cost effective and timely manner. The system must be easily convertible from one product to another and the production capacity must be readily scalable to produce more products on the existing system, exactly when the market needs them [29]. Convertibility is the system's ability to adjust production functionality quickly or change from one product to another [25]. Scalability allows the system's throughput capacity to be readily adjusted to abrupt changes in market demand [23]. These characteristics differ in that convertibility concerns the transformation of a system's functionalities while scalability concerns the modification of production capacity. Besides this, convertibility includes contributions concerning machines, their arrangements or configuration and material handling devices, and scalability refers to the adjustment of structure, at the system level (adding or removing machines) and at the machine level (changing a machine's hardware and control software, e.g. adding spindles, adding axes, or changing tool magazines) [29]. However, these core RMS characteristics may merge because both are directly related to a manufacturing system's responsiveness to sudden changes: convertibility to changes in product mix and scalability to changes in demand. Additionally, both characteristics must be considered at the project stage of RMS, which must be designed at the outset for future expansion in its functions and throughput capacity, to enable changes in supply exactly when needed by the market [23].

The existence of five core characteristics regarding a system's reconfigurability is supported by the early studies on RMS, which considered modularity, integrability, customization, convertibility and diagnosability as the essentials [3,6,18,21]. Nevertheless, these first definitions of convertibility concerned only the changeover between products and batches, changes of tools, part-programs and fixtures, and system adaptations for new products. Despite considering the structural adjustment at the machine level, which is a partial description of scalability, they did not include the needs at the system level, i.e., the addition or removal of resources to readily adapt the system's throughput capacity for future expansion. For this reason, the description of convertibility does not fit that construct that merged convertibility and scalability measures. A more suitable definition, gathering and generalizing both main abilities, is adaptability, that can be defined as the property of a manufacturing system that enables it to adapt its capacity and functionality by means of an adjustable structure to changed or new situations. This permits a short term resetting of the system to produce different variants of current products or new products, and guarantees a high long-term benefit-to-cost-ratio [3]. Adaptability is commonly related to a system's arrangement and its physical configuration, and is considered at the system's design stage, as well as convertibility and scalability.

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

4.2. The implementation level of RMS core characteristics

In Table 5, a summary of the respondents' perceptions of the implementation level of the variables investigated is presented. These core characteristics determine the time, the effort and the cost of the reconfiguration process and enable a rapid response to sudden market changes [3,10].

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

Diagnosability was the characteristic ranked third. The manufacturing systems of the respondent companies include inspection resources that allow the detection of quality or reliability problems and defective products in real time, as well as the diagnosis of their root causes and the resetting of their parameters to restore the initial situation or adjust its parameters. A rapid tuning to new conditions is essential to produce quality products. Indeed, performing in-process diagnostics may dramatically shorten the ramp-up time after reconfigurations and it allows the rapid identification of problems with quality and reliability during normal production. Additionally, the respondents perceive lower implemented levels of integrability and modularity. The majority assumed that companies have difficulties in easily, rapidly and precisely integrating a control system, new equipment or new technologies. Ideal RMS are able to integrate machine tools, sub-assemblies and sub-systems in changed manufacturing scenarios, exchange real time information, including their status and become participative in enhancing system efficiency [19].

The lack of machine tool design methodology and the lack of interfaces increase the barriers that impede modularity [3]. These are possible reasons why modularity was listed as the least ranked characteristic. The companies surveyed reported that the most important equipment is not composed by modules, cannot be easily reorganized to obtain an adapted structure to manufacture new products, nor be easily added or removed from the shop floor. Despite the aim to develop designs with different detachable modules for rapid and easy reconfiguration, efficient upgradation and other engineering objectives, each objective may require different modularisation, thus increasing the costs of the implementation of modularity [19].

While customization and adaptability reduce reconfiguration costs and were considered as critical characteristics of RMS, diagnosability, integrability and modularity support RMS characteristics, minimize reconfiguration time and effort and allow rapid reconfiguration, but they do not guarantee modifications in production capacity and functionality [10,13]. Note that the two critical characteristics of reconfigurability (customization and adaptability) appear to be more implemented than the other three characteristics (modularity, integrability and diagnosability). A *t*-test was performed showing that there is a statistical significant difference, at a 99% level, between the means of the two first variables and of the last three variables.

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

Novel technologies preconized in the concept of industry 4.0 might help to increase the level of implementation of these three RMS core characteristics. In fact, in industry 4.0, production systems evolve to Cyber Physical Production Systems (CPPS), which comprise smart machines, warehousing systems and production facilities that have developed digitally and feature end-to-end integration. By using data analytic tools, control charts statistical knowledge and intelligent algorithms, data can be processed to provide valuable information for manufacturers [9]. These technologies and the principle of 3D scanning for automated quality inspection may contribute to real time processing, enabling diagnosability. However, these technologies possesses drawbacks, such as the high cost of the devices, limited point per second scanning volume, and need for high-capability hardware for data processing [9].

Although integrability implies a mutual information and communication system for all equipment and organizational functions, the current production scenario in many companies seem to have multiple protocols, with the associated problems that this may bring. CPPS can bring together virtual and physical worlds to create a truly networked world in which intelligent objects communicate and interact with one another. Thus, standardized data communication protocols and information modelling methods may be used to address this issue [9]. On the other hand, integrability also needs mechanical and physical systems, including transportation systems, which ease the introduction of new equipment. The use of radio frequency identification devices (RFID), sensors and cameras attached to critical components could facilitate the collection and transmission of real time data. Compatible information systems, reconfigurable controls and more flexible transportation systems, e.g., Automated Guided Vehicles (AGV), could also contribute to the increase of the systems' integrability. In addition, an open and integrated environment may enhance the data acquisition capabilities of devices and applications, and move towards a plug-and-play environment to reduce the cost of data integration [9].

Finally, modularity is still difficult to find in the majority of manufacturing equipment, although it is a key factor and should be included in the design phase. Lightweight equipment and mobile and collaborative robotics that facilitate rapid and easy addition to, or removal of, robots from tasks, may contribute to reinforcing this ability. Furthermore, technological advances in the field of industry 4.0 may overcome the difficulties of having a harmonized human-machine environment, which allows effective and profitable co-existence and cooperation [13,14].

Modular-based systems have many benefits that will make it possible to achieve the paradigm of reconfigurable manufacturing systems and the necessary mass customization. Due to its modularity, it is possible to achieve sufficient variety by combining different modules while significantly reducing the number of parts that need to be produced for a product family. Moreover, if the modularity is incorporated in the design process from the outset, the life cycle cost will be decreased. The greater the modularity is, the lower the life cycle cost will be, where standardized module interfaces have a positive impact as they harmonize the work content [13].

5. Conclusion and further research

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

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

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

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

The findings seem to suggest that the novel technologies preconized by the concept of industry 4.0, such as big data analysis and real time collection, flexible transportation systems or mobile and collaborative robotics, might significantly contribute to the increase of manufacturing systems reconfigurability.

In practical terms, the questionnaire developed can be used by managers to assess the degree of reconfigurability of their production systems and for internal and external benchmarking. Furthermore, this paper highlights some current technological advances, discussing how they can contribute to improve each of the core characteristics of RMS. The sum of RMS core characteristics determines the ease and the cost of reconfiguring manufacturing systems. Thus, knowing the level of implementation of each core characteristic and how each one can be improved might help managers to decide strategies to increase the reconfigurability of their production systems.

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

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Appendix. Questionnaire

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

Section A

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

A1 *How would you describe the complexity of the dominant activity?*

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

[1]The modular design describes a product made up of standardized 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.

A2 *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 characterized 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

A3 *Select the statement that best fits your production system.*

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

A4 *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

A5 *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

A6 *How is the layout configuration of your dominant activity characterized?*

☐	Process layout
☐	Product layout
☐	Cellular layout

Section B

Remember to answer considering the plant's dominant activity.

B1 *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 reorganized to obtain an adapted configuration to manufacture new products	1	2	3	4	5	6	7
Our material handling system (between workstations) allows an easy rearrangement of the process flow, by adding/ignoring operations, according to the product to be manufactured*	1	2	3	4	5	6	7
Our manufacturing system is composed by hardware and software modules that can be integrated quickly and reliably*	1	2	3	4	5	6	7

B2 *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

B3 *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 customized to have the exact control functions needed	1	2	3	4	5	6	7

B4 *To what extent do you agree with the following statements?*

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

B5 *To what extent do you agree with the following statements?*

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

B6 *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

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

References

[1] Kusiak A. Flexible manufacturing systems: a structural approach. Int J Prod Res 1985;23:1057–73.
[2] Maccarthy BL, Liu J. A new classification scheme for flexible manufacturing systems. Int J Prod Res 1993;31:299–309.
[3] Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, et al. Reconfigurable manufacturing systems. CIRP Ann Manuf Technol 1999;48:527–40.
[4] ElMaraghy HA. Flexible and reconfigurable manufacturing systems paradigms. Int J Flex Manuf Syst 2006;17:261–76.
[5] Koren Y, Gu X, Guo W. Reconfigurable manufacturing systems: principles, design and future trends. Front Mech Eng China 2018;13:121–36.
[6] Abdi MR, Labib AW. A design strategy for reconfigurable manufacturing systems (RMSs) using analytical hierarchical process (AHP): a case study. Int J Prod Res 2003;41:2273–99.
[7] Gumasta K, Gupta SK, Benyoucef L, Tiwari MK. Developing a reconfigurability index using multi- attribute utility theory. Int J Prod Res 2011;49:1669–83.
[8] Leitão P, Barbosa J, Trentesaux D. Bio-inspired multi-agent systems for reconfigurable manufacturing systems. Eng Appl Artif Intell 2012;25:934–44.
[9] Zheng P, Wang H, Sang Z, Zhong RY, Liu Y, Liu C, et al. Smart manufacturing systems for Industry 4.0: conceptual framework, scenarios, and future perspectives. Front Mech Eng China 2018;13:137–50.
[10] Koren Y, Shpitalni M. Design of reconfigurable manufacturing systems. Int J Ind Manuf Syst Eng 2010;29:130–41.
[11] Wang GX, Huang SH, Yan Y, Du JJ. Reconfiguration schemes evaluation based on preference ranking of key characteristics of reconfigurable manufacturing systems. Int J Adv Manuf Technol 2017;89:2231–49.
[12] Nishith M, Rishi G, Sharma SK. Flexibility measurement criteria with respect to reconfigurable system properties. Int J Eng Res Appl 2013;3:1711–6.
[13] Benderbal HH, Dahane M, Benyoucef L. Modularity assessment in reconfigurable manufacturing system (RMS) design: an Archived Multi-Objective Simulated Annealing-based approach. Int J Adv Manuf Technol 2018;94:729–49.
[14] Andersen AL, Brunoe TD, Nielsen K, Rösiö C. Towards a generic design method for reconfigurable manufacturing systems: analysis and synthesis of current design methods and evaluation of supportive tools. Int J Ind Manuf Syst Eng 2017;42:179–95.
[15] Wiendahl H-P, ElMaraghy HA, Nyhuis P, Zäh MF, Wiendahl H-H, Duffie N, et al. Changeable manufacturing - classification, design and operation. Ann CIRP 2007;56:783–809.
[16] Bi ZM, Lang SYT, Shen W, Wang L. Reconfigurable manufacturing systems: the state of the art. Int J Prod Res 2008;46:967–92.
[17] Benderbal HH, Dahane M, Benyoucef L. Flexibility-based multi-objective approach for machines selection in reconfigurable manufacturing system (RMS) design under unavailability constraints. Int J Prod Res 2017;55:6033–51.
[18] Mehrabi MG, Ulsoy AG, Koren Y. Reconfigurable manufacturing systems: key to future manufacturing. J Intell Manuf 2000;11:403–19.
[19] Singh A, Gupta S, Asjad M, Gupta P. Reconfigurable manufacturing systems: journey and the road ahead. Int J Syst Assur Eng Manage 2017;8:1849–57.
[20] Renzi C, Leali F, Cavazzuti M, Andrisano AO. A review on artificial intelligence applications to the optimal design of dedicated and reconfigurable manufacturing systems. Int J Adv Manuf Technol 2014;72:403–18. https://doi.org/10.1007/s00170-014-5674-1.
[21] Setchi RM, Lagos N. Reconfigurability and Reconfigurable Manufacturing Systems - state-of-the-art review. Ind Informatics, 2004 INDIN' 04 2004 2nd IEEE Int Conf 2004:529–35.
[22] Padayachee J, Bright G. Synthesis of evolving cells for reconfigurable manufacturing systems. IOP Conf Ser Mater Sci Eng 2014;65:12009–17.
[23] Koren Y, Wang W, Gu X. Value creation through design for scalability of reconfigurable manufacturing systems. Int J Prod Res 2016;55:1227–42.
[24] Liu JP, Luo ZB, Chen K, Liu SJ. Diagnosability measures throughout the total process of a reconfigurable manufacturing system. Procedings 7th Int. Conf. Ind. Eng. Eng. Manag.. 2000. p. 394–8.
[25] Maier-Sperredelozzi V, Koren Y, Hu SJ. Convertibility measures for manufacturing systems. CIRP Ann Manuf Technol 2003;52:367–70.
[26] Farid AM. Measures of reconfigurability and its key characteristics in intelligent manufacturing systems. J Intell Manuf 2017;28:353–69.
[27] Mehrabi MG, Ulsoy AG, Koren Y, Heytler P. Trends and perspectives in flexible and reconfigurable manufacturing systems. J Intell Manuf 2002;13:135–46.
[28] Spena PR, Holzner P, Rauch E, Vidoni R, Matt DT. Requirements for the design of flexible and changeable manufacturing and assembly systems: a SME-survey. Procedia Cirp 2016;41:207–12.
[29] Koren Y. The rapid responsiveness of RMS. Int J Prod Res 2013;51:6817–27.
[30] Meng G, Heragu SS, Zijm H. Reconfigurable layout problem. Int J Prod Res 2004;42:4709–29.
[31] Dillman DA. Mail and internet surveys: the tailored design method. 2nd ed. New Jersey: JohnWiley & Sons, Inc.; 2007.
[32] Forza C. Surveys. In: Karlsson C, editor. Res. methods oper. manag. 2nd ed.New York: Routledge; 2016. p. 79–164.
[33] Wang W, Koren Y. Scalability planning for reconfigurable manufacturing systems. Int J Ind Manuf Syst Eng 2012;31:83–91.
[34] Comission European. The new SME definition: user guide and model declaration. Off J Eur Union 2005;C:1–52. doi:EN NB60-04-773-ENC-C 92-894-7909-4.
[35] Carmines EG, Zeller RA. Reliability and validity assessment. Ohio, USA: Sage Publications, Inc; 1979.
[36] Cronbach LJ. Coeficient alpha and the internal structure of tests. Psychometrika 1951;16:297–334.
[37] Nunnally JC, Bernstein IH. Psychometric Theory. 1994.
[38] Hair JF, Black WC, Babin BJ, Anderson RE. Multivariate data analysis. 7th ed. Pearson Prentice Hall; 2010.
[39] Malhotra MK, Grover V. An assessment of survey research in POM: from constructs to theory. J Oper Manage 1998;16:407–25.