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Antecedents and enablers of supply chain reconfigurability and their effects on performance

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Abstract

The reconfiguration of supply chain is becoming a crucial concept used to deal with market disruptions and changes such as the COVID-19 pandemic, demand uncertainty, and new technologies. It can be defined as the ability of the supply chain to change its structure and functions in order to adapt to new changes. Its assessment requires an understanding of its quantitative factors to provide indicators that are easy to interpret. Effective reconfigurability assessment can be achieved by measuring quantitatively its six characteristics (modularity, integrability, convertibility, diagnosability, scalability, and customization). This paper aims at identifying the quantitative factors of each characteristic and their inter-relationships by using Total Interpretive Structural Modelling (TISM). The structural model obtained by TISM is applied to understand the dependency quantitative factors. Based on TISM results, a classification of quantitative factors is determined using "Matrice d'Impacts Croisés, Multiplication Appliquée à un Classement" (MICMAC) analysis. This article provides a better understanding of the six characteristics previously mentioned to improve the reconfigurability of supply chains by considering the interactions between their factors. Thus, this analysis helps managers to understand the characteristics that influence the change of the supply chain structure and those that enable changing the supply chain functions in order to optimize the supply chain reconfiguration process.

Keywords Reconfigurable supply chain · Performance evaluation · Quantitative factors · Supply chain management · Reconfigurability · TISM · MICMAC

1 Introduction

Nowadays, the COVID-19 pandemic and many other hazards reveal the inability of the existing supply chains to cope with unforeseen risks. Consequently, several supply chain strategies need to be reconsidered. For example, reshoring is a core element in the supply chain reconfiguration strategy [1, 2]. It needs to be reconsidered to deal with the disruptions caused by the COVID 19 pandemic [3, 4]. In addition, supply chain uncertainties, demand fluctuations, and technological change are leading manufacturers to adapt the adequate supply that makes them competitive. To meet these challenges, the implementation of a Reconfigurable Supply Chain (RSC) ensures the survival of the company in changing environment [5, 6]. RSC designates the ability of supply chain to change its structure and its functions to cope with disruptions. The latter is defined as unexpected events that impact the supply chain performance [7, 8]. Although disruption risks are rare events, they highly affect the supply chain [7, 9–12].

The changes affecting supply chain configuration are related to partner positions within the networks and the role of the central network organization [13]. Reconfiguration in supply chain combines a positive side indicating the innovation and the negative side indicating disruption risks, that is why it is important to innovate for disruption recovery [14]. In fact, the innovation is linked to the implementation of new technologies. [15] showed the crucial role of additive manufacturing technologies in supply chain reconfiguration strategies. RSC ensures the flexibility and agility

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of the supply chain by altering its configurations with the minimum resources [16]. Reconfigurability is characterized by modularity, convertibility, integrability, diagnosability, scalability, and customization [17, 18]. These characteristics result in a truly reconfigurable supply chain [18]. Hence, it is necessary to assess the degree of reconfigurability through its characteristics to determine if the supply chain can easily and quickly change its structure and functions to cope with disruptions [19, 20]. Several indicators have been proposed to measure reconfigurability for machine, cell, and system reconfiguration. However, the measuring of the supply chain capacity to cope with disruptions was not given great interest by the research community. In this paper, the previously mentioned reconfigurability characteristics are considered as the performance indicators for assessing the degree of reconfigurability. This assessment requires the identification of some factors to quantify each characteristic to help decision-makers determine the capacity of their supply chains to cope with events that may affect the supply chain performance.

In [19], we proposed six metrics to measure the degree of reconfigurability by considering modularity, integrability, convertibility, diagnosability, scalability, and customization as key indicators of reconfigurability. In order to provide managers and decision-makers with a tool to quantitatively and objectively evaluate supply chain reconfigurability, while dealing with information uncertainty in the supply chain, [20] proposed a reconfigurability evaluation approach based on the six metrics using fuzzy logic.

The choice of reconfigurability characteristics as indicators to assess reconfigurability proved the possibility to effectively assess the ability of the supply chain to change its structure and functions to cope with market changes. For this purpose, we propose a detailed analysis of reconfigurability characteristics and its quantitative factors. The analysis aims to improve the reconfigurability evaluation model by studying the interactions between the quantitative factors related to reconfigurability characteristics that will give more details and

data on them. Figure 1 illustrates the difference between our new approach in this article and our previous research work.

The purpose of this paper is to specify factors related to modularity, convertibility, integrability, diagnosability, scalability, and customization, which allows measuring the degree of reconfigurability.

The rest of the paper is organized as follows. In Sect. 2, the related works are surveyed. Section 3 presents the proposed methodology applied to identify the quantitative factors of each reconfigurability characteristic and analyze the inter-relationships between them. The obtained results are discussed in Sect. 4. Section 5 highlights the managerial and practical implications of the proposed approach. Finally, Sect. 6 concludes the paper.

2 Literature review

2.1 The concept of reconfigurability

Today's market environment is characterized by high competition and rapid change, which drives companies to implement new technologies that offer high flexibility and agility. New technologies are a major advantage for manufacturers in their strategies to adapt to changing market needs. Decision-makers are looking for these technologies to adjust their systems, from a structural and functional point of view to new requirements through dynamic reconfiguration. To remain competitive, manufacturing firms must respond quickly to fluctuating market demand by introducing products that meet customer needs [21]. In fact, the need to introduce new products, changing product structures, fluctuating demand, and the continuous emergence of new technologies have given rise to the concept of "Reconfigurability" manufacturing systems called Reconfigurable Manufacturing System (RMS) characterized by modularity, integrability, convertibility, diagnosability, and
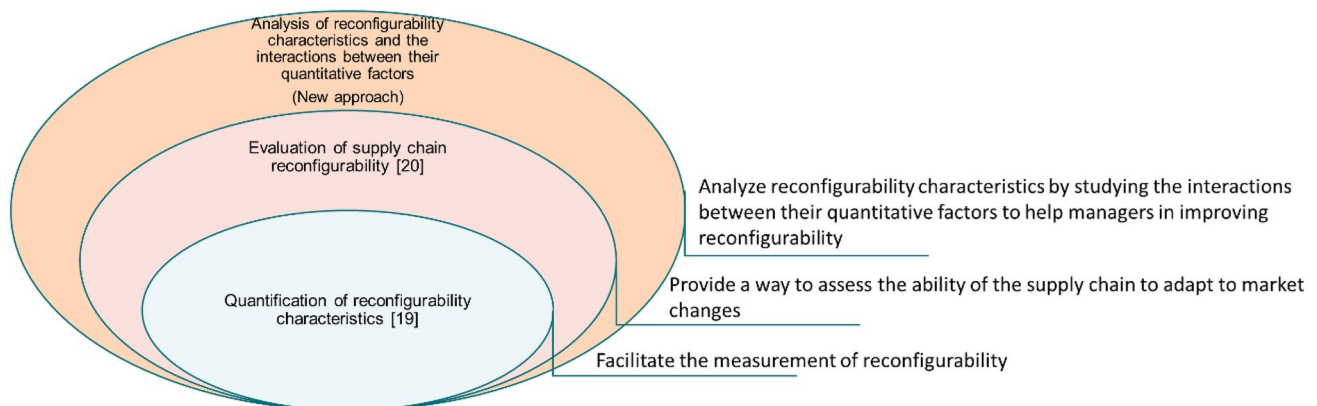

Fig. 1 The novelty of the proposed approach

scalability [22]. Reconfigurability refers to the practical ability of a production or assembly system to change to a particular number of parts or sub-parts by adding or removing functional elements reactively and with minimal effort and delay [23]. Thus, it refers to the ability to repeatedly modify and reorganize the components of a system [24].

Reconfigurability represents a form of changeability that can be applied at the equipment, production system, and assembly system level to dynamically and efficiently change the capabilities and functionality of the system [25–27]. Beyond machines and system components, reconfigurability includes the ability to reconfigure resources quickly and efficiently to generate and deploy new configurations that cope with the new environment [28].

At a higher level, reconfigurability can be applied at the supply chain level. It is defined as the ability of supply chain to change its structure and its functions to cope with disruption and market changes [19, 29]. Indeed, the guarantee of reconfigurability is mainly due to its six characteristics that allow reducing the reconfiguration effort. [19, 20, 30] consider that these characteristics allow judging and evaluating the capacity of the supply chain to adapt to the new requirements. Therefore, it is necessary to study the analogy between the characteristics at the RMS level and those at the RSC level.

From another point of view, the form of network governance can influence the dynamics of companies, namely the decision-making processes of supply chain reconfiguration [31]. Indeed, each company participating in a network must take into consideration the capabilities and specificities of other firms and how they can contribute to increasing the competitiveness of the network. In the same perspective, these effective sustainability strategies require the understanding of customers' needs and the resolution of problems quickly and efficiently, as highlighted by [32]. This shows that the reconfiguration of production networks and supply chains requires the assurance of effective sustainability. Some strategies have been evoked in the literature to point out the importance of the sustainability of production networks to support reconfiguration. [33] cited four strategies that guarantee the survival of firms in a changeable and risky environment:

– "Employment, training, and retention of high-quality staff members;
– Prevalence of good products, services, and optimum timing in introducing these into the marketplace;
– Excellent relationships with customers;
– Availability of top managers with good leadership qualities."

Some strategies can be deployed to support reconfiguration in order to be competitive, including environmental

advantage, diversity, and consolidation. Indeed, in order to adapt to market changes and survive economic downturns [34], companies must adopt alignment strategies that focus on meeting customer needs by ensuring good communication with all stakeholders [35]. Second, the participative strategy focuses on idea creation by ensuring internal communication with employees. Also, the focus on ideas in case of lack of variety is called the simplistic strategy.

To remain competitive in an uncertain and competitive market, [31] studied the crucial elements for responding to these issues such as self-management for network configuration and development. At the level of resources and capabilities, the interactions between companies and the optimization of resources allow guaranteeing competitiveness. Concerning relationships and collaborations, the authors suggest establishing alliances between stakeholders. In this context, [36] mentioned that the development of information and communication technologies allows responding to market changes and remains competitive by ensuring cooperation strategies that guarantee information sharing. Finally, for the creation of value, it is recommended to create value through collaborative strategies to innovate and offer diversified products.

The choice of modularity, integrability, convertibility, diagnosability, scalability, and customization as indicators for measuring and evaluating reconfigurability has proved its effectiveness in the several case studies conducted in the context of RMS and RSC. Indeed, these case studies have been carried out in several industrial sectors that have implemented reconfigurable systems namely [37] which proposed a qualitative model that allows evaluating the degree of reconfigurability in an automotive company. In addition, [38] conducted a case study in an automotive industry to evaluate the reconfigurability of the system through its six characteristics. On a larger level, [39] proposed a model for evaluating reconfigurability in the supply chain that was implemented and tested in A multi-national automotive supply chain aimed at meeting the demand in the Indian market. Also, [20] conducted a case study in a pellet stove distribution company that decided to reconfigure its supply chain to meet the increased demand. In this case study, a comparison between two possible new configurations was proposed by evaluating their degree of reconfigurability according to the metrics proposed in [19].

2.2 The characteristics of reconfigurability: from RMS to RSC

2.2.1 Modularity

Modularity is generally used to reduce the complexity of the system through a decomposition based on the interactions existing between its components. In reconfigurable systems, it is measured through the degree of coupling, which

designates the interactions between modules, and cohesion which indicates the interactions within modules [40–46]. The objective of modularity is to maximize cohesion and minimize coupling. In RSCs, modularity aims at clustering the activities of the supply chain by taking into account the flows connecting them [47]. It ensures the independence between modules through the standardization of interfaces [48, 49]. In fact, the supply chain modularity is measured by the degree of non-proximity (geographic, organizational, cultural, and electronic) [50]. Quantitative factors proposed to measure the degree of modularity are the numbers of modules, the intra- and inter-module interactions, and the lead time.

2.2.2 Convertibility

To cope with disruptions, the system should be made up of components that can be easily converted to adapt quickly to new changes. In reconfigurable manufacturing systems, convertibility is measured based on the increment of conversion, the routing connections, and the replicated machines [51]. The system's capability to be autonomous is also a quantitative factor that must be considered to measure convertibility [52]. To easily convert supply chain components, it is necessary to have redundant entities to quickly deal with disruption [53]. Indeed, supply chain redundancy is the quantitative factor of convertibility measurement in RSC.

2.2.3 Integrability

Adjustment cost and time are key factors in measuring integrability in RMS [46]. They can be reduced by the standardization of interfaces. The complexity of the latter may, in turn, minimize the complexity of the supply chain composed of a set of nodes and flows that represent the connections between nodes [54, 55]. [56] explained the impact of product complexity on supply chain network that can negatively impact collaborative strategies with suppliers in the supply chain. It is due to a large number of actors and interconnections between them [57]. Quantitative factors allowing integrability measurement in RSC are number of nodes and number of connections.

2.2.4 Diagnosability

In order to detect and correct failures quickly, the reconfigurable system must have a high degree of RMS diagnosability that can be measured using the three following parameters:

- Detectability which determines the time before detecting the failure;

- Predictability which measures the time before the failure re-occurrence;
- Distinguishability which measures the time necessary to identify the replaceable unit of a system that causes a failure [42].

Diagnosability is also measured based on the accuracy of the quality tests on products during ramp-up time [46]. Indeed, the quality of the information transmitted in the system provides a better visibility on the system's state and, consequently, it allows a rapid detection of failures. In supply chain, this parameter is measured as a function of the quantity, accuracy, and freshness of the information [58]. Based on the above reasoning, RSC diagnosability is measured by considering two quantitative factors: supply chain visibility and detection time.

2.2.5 Scalability

In RMS, if the system is able to satisfy the customer demand with small capacity adjustments, then the RMS will have a high scalability and vice versa [46]. Scalability can be measured by the effectiveness of the system [59] and by the adjustment value needed to achieve the maximum capacity which depends on the reconfiguration cost and time [46]. Scalability in the supply chain depends on latency, the ability to achieve performance objectives in a dynamic and uncertain environment, and data quality [60]. The impact of scalability on supply chain performance can be expressed by delay [61]. Hence, RSC scalability can be measured by two quantitative factors: latency and throughput capacity.

2.2.6 Customization

Customization depends on customization activities showing customer involvement in the realization of products, which is a key factor that should be considered to measure the degree of customization in the supply chain [62]. Its degree can be increased by minimizing the response time [63, 64]. Indeed, customization can be measured based on several indicators such as [65] the value-added time, the throughput rate, and the average number of customizable functions. In RMS, two aspects must be taken into account in cutomization assessment: the product and the functionality which designates the machine utilization rate [46]. Based on this analysis, the quantitative factors of customization measurement are the response time and the number of customized functions.

As shown in Table 1, the identified quantitative factors of each RSC characteristic are summarized.

3 Proposed approach

Literature studies were carried out to identify factors for a quantitative measure of reconfigurability characteristics. Based on the results presented in the literature review, the first stage of the proposed approach is to determine the interactions between all the quantitative factors of each RSC characteristic using the TISM method. An interaction is a mutual or reciprocal action or influence. It can be related to the enterprise internal flows and external flows linking all supply chain actors. These flows can be physical, informational, and financial. The second stage consists in identifying the most important quantitative factors. This classification allows identifying the most important characteristics in the supply chain reconfiguration process. Figure 2 shows the different steps of our approach.

Even if the TISM method requires the judgments of the decision-makers, the results of our approach will not be impacted by the subjectivity of this method because the identified relationships between the quantitative factors related to the reconfigurability characteristics do not impact the reconfigurability evaluation model. Indeed, our aim is to identify the possible interactions between the quantitative factors to better analyze the reconfigurability characteristics and to provide a way for managers to see the importance of each characteristic in improving reconfigurability. As pointed out by [16], configuration and reconfigurability problems are difficult to validate, and require the integration of decision-makers' judgments because the decision-making process is long.

3.1 Development of inter-relationships among the quantitative factors using TISM

The TISM method is applied to identify contextual relationships between the identified quantitative factors. It consists in defining the relationships between the quantitative factors, by developing structural and reachability matrices in order to classify the quantitative factors according to different levels.

3.1.1 Development of the Structural Self-Interaction Matrix (SSIM)

To determine the influences between the quantitative factors related to each reconfigurability characteristic, a questionnaire was conducted and addressed to a group of experts and academics. The questionnaire is used to analyze the influences between the identified factors, and thus to build SSIM. Eleven experts and academics participated in the questionnaire, where 36.4% have less than 10 years of experience, 36.4% also have experience between 10 and 20 years, while 27.3% have more than 20 years of experience. A classification of the experts' profiles is presented in Table 2.

This matrix is used to define any relationship between two quantitative factors. Four symbols are employed to indicate the direction of the relationship (i, j), as shown in Table 3, with:

Table 1 Quantitative factors of RSC characteristics

Characteristics	ID	Quantitative factors	Definition
Modularity	M1	Number of modules	The number of modules/units obtained after the modular decomposition
	M2	Intra- and inter-module interactions	The number of links connecting the different modules and the elements of each module
	M3	Lead time	Corresponds to the time between the ordering of a supplier and the delivering of goods to the customer
Convertibility	CO1	Supply chain redundancy	Consists in providing additional capacity to avoid delays or stops due to disruptions
Integrability	I1	Number of nodes	Refers to the number of companies coordinating the management of goods (purchase, stock, transport…) within the same supply chain
	I2	Number of connections	Refers to the number of interactions between the nodes of the supply chain
Diagnosability	D1	Supply chain visibility	Is the sharing of information in a just-in-time, reliable, and accurate manner
	D2	Detection time	The time measured from the moment when a company realizes that it will be affected by a supply chain disruption to the moment in which the incident really occurs
Scalability	S1	Latency	It is the ratio between the delivery time and the throughput time
	S2	Throughput capacity	Designates the number of the performed orders
Customization	CU1	Response time	It is the total amount of time spent to respond to a request for service
	CU2	Number of customized functions	Designates the number of functions related to the customization of the product/service

Fig. 2 Proposed approach of identification and analysis of the quantitative factors of RSC characteristics
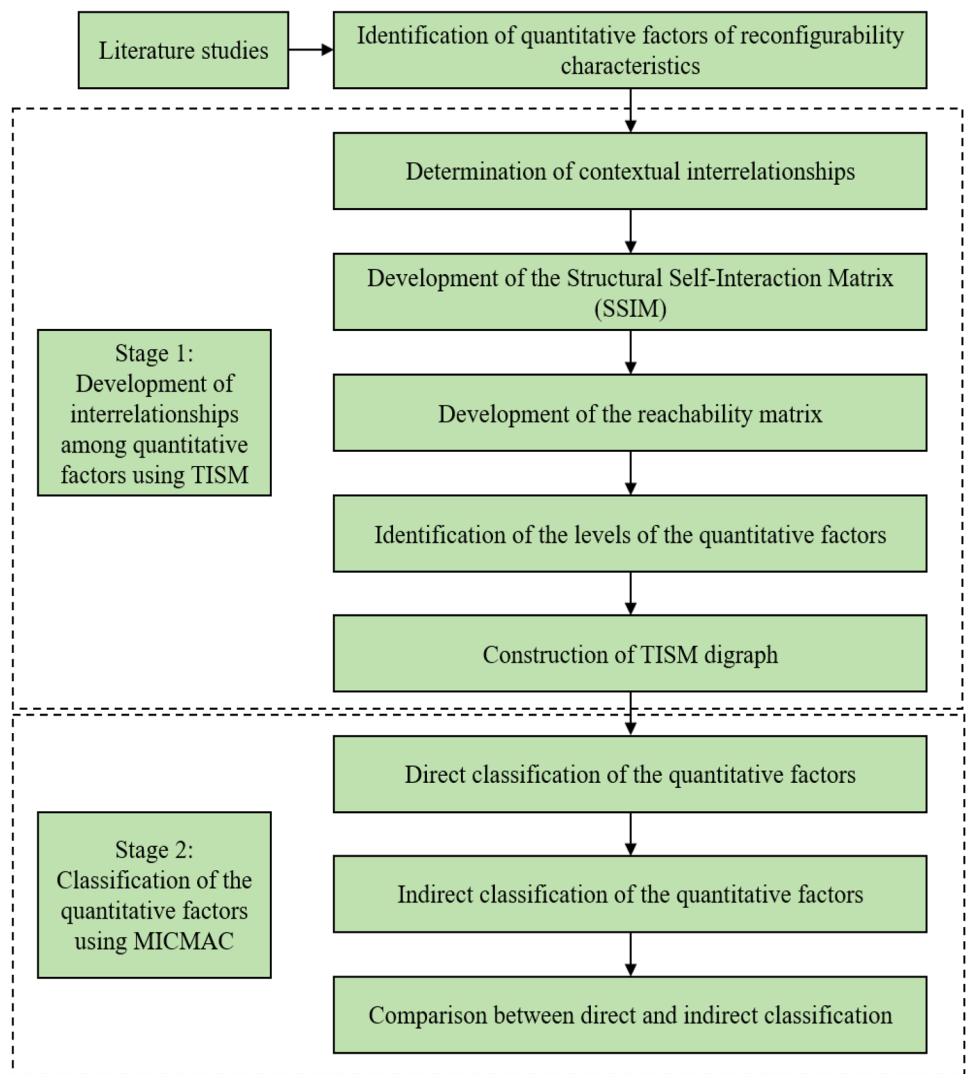
- V means that the quantitative factor i "will influence" the quantitative factor j;
- A indicates that the quantitative factor i 'is influenced" by the quantitative factor j;
- X shows that the quantitative factors i and j influence each other;

- O reveals that the quantitative factors i and j are not related.

3.1.2 Development of the reachability matrix

Based on the SSIM, we replace V, A, X, and O by 1 or 0. The applied conversion rules are presented below:

- If the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix is 1 and the (j, i) entry is 0;
- If the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix is 0 and the (j, i) entry is 1;
- If the (i, j) entry in the SSIM is X, then the (i, j) and (j, i) entry in the reachability matrix is 1;
- If the (i, j) entry in the SSIM is O, then the (i, j) and (j, i) entry in the reachability matrix is 0.

The transitivity is also checked in the rules of the matrix. If a relationship exists between the first and second

Table 2 Expert's profile

Profile	Category	Number of experts
Experience	Less than 10 years	36.4%
	Between 10 and 20 years	36.4%
	More than 20 years	27.3%
Field	Supply chain	90.9%
	Transport	72.7%
	Production	54.5%
	Academic	18.2%

Table 3 Formation of SSIM

	CU2	CU1	D2	D1	S2	S1	CO1	I2	I1	M3	M2	M1
M1	V	V	V	V	V	V	V	X	X	V	X	X
M2	V	V	V	V	V	V	V	X	X	V	X	
M3	A	A	O	O	X	X	O	A	A	X		
I1	V	V	V	V	V	V	V	X	X			
I2	V	V	V	V	V	V	V	X				
CO1	O	O	V	V	O	O	X					
S1	O	O	O	O	X	X						
S2	O	O	O	O	X							
D1	V	V	X	X								
D2	V	V	X									
CU1	X	X										
CU2	X											

variable and between the second and third variable, then there is a relationship between the first and third variable. The obtained matrices are presented in Tables 4 and 5.

3.1.3 Identification of the levels of the quantitative factors

The obtained accessibility matrix is divided into reachability and antecedent sets, as shown in Tables 6, 7, 8, and 9.

3.1.4 TISM model

Quantitative factors are organized graphically in levels and directed links are represented according to the relationships identified in the reachability matrix. The relationship between elements *i* and *j* can be represented by an arc from *i* to *j*. Figure 3 shows the structure of quantitative factors.

The number of modules, the number of interactions, the number of nodes, the number of inter- and intra-module interactions, and the supply chain redundancy are put at the bottom of the model, which means that these factors affect other factors and are not affected by none of them and are

not influenced by any factors. Thus, they are very important and need to be primarily taken into account for a better reconfigurability in supply chains. At a higher level, supply chain visibility and detection time represent the second level. These factors interact with the next block constituted by the response time and the number of customized functions that represent the third level, which are homogeneous and influence each other. Finally, the lead time, latency, and throughput capacity are in the highest level of the TISM graph. Indeed, they are influenced by all the other enablers, and they affect them slightly.

3.2 Classification of the quantitative factors using MICMAC analysis

This stage consists in identifying the quantitative factors, i.e., those that are essential for the development of the system, first by direct classification (easy to implement) and then by indirect classification (by MICMAC). The MICMAC analysis is used to classify and validate the factors identified in the TISM.

Table 4 Initial reachability matrix

	M1	M2	M3	I1	I2	CO1	S1	S2	D1	D2	CU1	CU2
M1	1	1	1	1	1	1	1	1	1	1	1	1
M2	1	1	1	1	1	1	1	1	1	1	1	1
M3	0	0	1	0	0	0	1	1	0	0	0	0
I1	1	1	1	1	1	1	1	1	1	1	1	1
I2	1	1	1	1	1	1	1	1	1	1	1	1
CO1	0	0	0	1	1	1	0	0	1	1	0	0
S1	0	0	1	0	0	0	1	1	0	0	0	0
S2	0	0	1	0	0	0	1	1	0	0	0	0
D1	0	0	0	0	0	0	0	0	1	1	1	1
D2	0	0	0	0	0	0	0	0	1	1	1	1
CU1	0	0	1	0	0	0	0	0	0	0	1	1
CU2	0	0	1	0	0	0	0	0	0	0	1	1

Table 5 Final reachability matrix

	M1	M2	M3	I1	I2	CO1	S1	S2	D1	D2	CU1	CU2
M1	1	1	1	1	1	1	1	1	1	1	1	1
M2	1	1	1	1	1	1	1	1	1	1	1	1
M3	0	0	1	0	0	0	1	1	0	0	0	0
I1	1	1	1	1	1	1	1	1	1	1	1	1
I2	1	1	1	1	1	1	1	1	1	1	1	1
CO1	1*	1*	1*	1	1	1	1*	1*	1	1	1*	1*
S1	0	0	1	0	0	0	1	1	0	0	0	0
S2	0	0	1	0	0	0	1	1	0	0	0	0
D1	0	0	1*	0	0	0	0	0	1	1	1	1
D2	0	0	1*	0	0	0	0	0	1	1	1	1
CU1	0	0	1	0	0	0	1*	1*	0	0	1	1
CU2	0	0	1	0	0	0	1*	1*	0	0	1	1

The 1* presented in Table 5 are included to incorporate transitivity

3.2.1 Direct classification of the quantitative factors

This step consists in filling the matrix of the direct influences, as shown in Table 6. Each element of this matrix is filled in according to the following scale:

- 0 means no influence;
- 1 means weak influence;
- 2 means medium influence;
- 3 means strong influence.

A first set of information can be obtained by analyzing the direct influences using the direct impact matrix. The sum of the values of each row and column indicates respectively the driving power and the dependency levels, as shown in Table 10.

The results of the direct influence matrix show that M1 (number of modules), M2 (number of inter- and intra-module interactions), I1 (number of nodes), I2 (number of interactions), and CO1 (supply chain redundancy) have the highest line sums; then, they represent the independent factors. In fact, M3 (lead time), S1 (latency), and S2 (throughput capacity) are dependent factors as they have the highest column sums.

Figure 4 shows the four quadrants indicating the four categories of factors obtained by the MICMAC analysis. The first quadrant includes the autonomous factors with low influence and low dependency such as D1 (supply chain visibility), D2 (detection time), CU1 (response time), and CU2 (number of customized functions). The second quadrant contains the dependent factors M3 (lead time), S1 (latency), and S2 (throughput capacity) having a low driving power

Table 6 Level partition (iteration I)

Factors	Reachability set	Antecedent set	Intersection set	Level
M1	M1, M2, M3, I1, I2, CO1, S1, S2, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
M2	M1, M2, M3, I1, I2, CO1, S1, S2, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
M3	M3, S1, S2	M1, M2, M3, I1, I2, CO1, S1, S2, D1, D2, CU1, CU2	M3, S1, S2	I
I1	M1, M2, M3, I1, I2, CO1, S1, S2, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
I2	M1, M2, M3, I1, I2, CO1, S1, S2, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
CO1	M1, M2, M3, I1, I2, CO1, S1, S2, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
S1	M3, S1, S2,	M1, M2, M3, I1, I2, CO1, S1, S2, CU1, CU2	M3, S1, S2,	I
S2	M3, S1, S2,	M1, M2, M3, I1, I2, CO1, S1, S2, CU1, CU2	M3, S1, S2,	I
D1	M3, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1, D1, D2	D1, D2	
D2	M3, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1, D1, D2	D1, D2	
CU1	M3, S1, S2, CU1, CU2	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	CU1, CU2	
CU2	M3, S1, S2, CU1, CU2	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	CU1, CU2	

Table 7 Level partition (iteration II)

Factors	Reachability set	Antecedent set	Intersection set	Level
M1	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
M2	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
I1	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
I2	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
CO1	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	
D1	D1, D2, CU1, CU2	M1, M2, I1, I2, CO1, D1, D2	D1, D2	
D2	D1, D2, CU1, CU2	M1, M2, I1, I2, CO1, D1, D2	D1, D2	
CU1	CU1, CU2	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	CU1, CU2	II
CU2	CU1, CU2	M1, M2, I1, I2, CO1, D1, D2, CU1, CU2	CU1, CU2	II

and a high dependency power. The third quadrant contains no factors which consists of the linking factors having high driving and dependency power. The fourth quadrant involves the independent factors with high influence and low dependency, such as M1 (number of modules), M2 (intra- and inter-module interactions), I1 (number of nodes), I2 (number of connections between nodes), and CO1 (supply chain redundancy). From the direct influence matrix, MICMAC generates a graph showing the most important influences, as shown in Fig. 5.

3.2.2 Indirect classification of the quantitative factors

The analysis of the indirect relationships allows detecting the essential and hidden factors and classifying the variables according to their influences by considering the global network of the relations described by the structural analysis matrix. The MICMAC analysis examines the influences between the variables to determine the indirect effects. These results show that the enablers M1 (number of modules), M2 (number of interactions between and within modules), I1 (number of nodes), I2 (number of interactions), and CO1 (supply chain redundancy) are driving enablers since they have the largest sum of lines. While M3 (lead time), S1 (latency), and S2 (throughput capacity) are the most influenced enablers (also called dependent enablers) because they have the highest sum of column. Table 11 summarizes the obtained results.

These results reveal that the enablers M1 (number of modules), M2 (number of inter- and intra-module interactions), I1 (number of nodes), I2 (number of interactions), and CO1 (supply chain redundancy) are driving enablers as they have the largest sums of lines. On the other hand, M3 (lead time), I1 (latency), and I2 (throughput capacity) are the most influenced enablers (also called dependent enablers) because they have the highest column sums.

The influential enablers and linking enablers are the same as those of the direct influence map. According to the indirect influence design, all factors keep the same position as in the direct design as demonstrated in Fig. 6. The influences of all the factors are represented in Fig. 7.

3.2.3 Comparison between direct and indirect classification

A comparison of the hierarchy of the quantitative factors of supply chain reconfigurability in the different classifications (direct and indirect) validates the importance of certain factors such as number of nodes, number of connections, number of modules, and supply chain redundancy in the supply chain reconfigurability assessment process.

MICMAC allows calculating numerical weights (direct influences/dependencies and indirect influences/dependencies) of reconfigurability enablers in supply chains and classifying them in descending order, as exposed in Tables 12 and 13.

From this comparison, we notice that enablers do not keep their rankings in the classification according to

Table 8 Level partition (iteration III)

Factors	Reachability set	Antecedent set	Intersection set	Level
M1	M1, M2, I1, I2, CO1, D1, D2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
M2	M1, M2, I1, I2, CO1, D1, D2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
I1	M1, M2, I1, I2, CO1, D1, D2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
I2	M1, M2, I1, I2, CO1, D1, D2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
CO1	M1, M2, I1, I2, CO1, D1, D2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
D1	D1, D2	M1, M2, I1, I2, CO1, D1, D2	D1, D2	III
D2	D1, D2	M1, M2, I1, I2, CO1, D1, D2	D1, D2	III

Table 9 Level partition
(iteration IV)

Factors	Reachability set	Antecedent set	Intersection set	Level
M1	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
M2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
I1	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
I2	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV
CO1	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	M1, M2, I1, I2, CO1	IV

direct and indirect influences and dependencies. Factors M1, M2, D1, D2, CU1, and CU2 have changed their rank in the indirect influence classification and have moved to higher ranks, which prove the importance of the indirect effect of these factors on the other factors. The green lines show the advancement in rank of the factors, while the red lines indicate its degradation. Moreover, we notice that the factors CO1, I1, I2, and M3 moved to lower ranks in the indirect influence classification. The influence of this factor decreases relatively when the indirect influences are considered. This classification allowed clarifying and validating the classification of factors obtained with TISM. Figure 8 represents the most highly reclassified factors and the rank variations for the most dependent factors. The variation in the positions of the enablers between their initial positions and their final positions is shown in Fig. 9.

This plan, represented in Fig. 9, shows the displacement of the influences of the factors which designates the change of the degrees of influence between the direct and indirect plans of the influences/dependencies. The results of the direct and indirect influences/dependencies analysis can be classified according to a comparison between the driving and dependent factors at the direct and indirect levels, as shown in Table 14. We note that all the factors kept their same position in the quadrants of the influence and dependency maps despite the variation in their degrees of influence.

4 Results and discussion

The aim of this study is to analyze and develop a model of mutual influences and relationship among factors allowing the assessment of reconfigurability. First, 12 quantitative factors were identified based on the literature. They were chosen based on each characteristic (modularity, integrability, convertibility, diagnosability, scalability, and customization) in order to facilitate their quantitative evaluations. To develop the SSIM matrix, a questionnaire was given to 11 experts and academics to determine the influences of all the identified factors. Then, the MICMAC analysis presents substantial information on the importance and interdependencies of these factors.

The TISM results show that the number of modules (M1), the number of inter- and intra-modules (M2), the number of nodes (I1), the number of connections (I2), and the supply chain redundancy (CO1) are factors that affect the other factors, but they are not influenced by any other factor. In fact, they influence the factors of the highest level including supply chain visibility (D1) and detection time (D2) that affect the factors of the second level: response time (CU1) and number of customized function (CU2). The highest level is composed of lead time, latency, and throughput capacity that represent factors not influencing any other factor. These findings were verified and validated by the MICMAC analysis. Based on the results obtained by the direct and

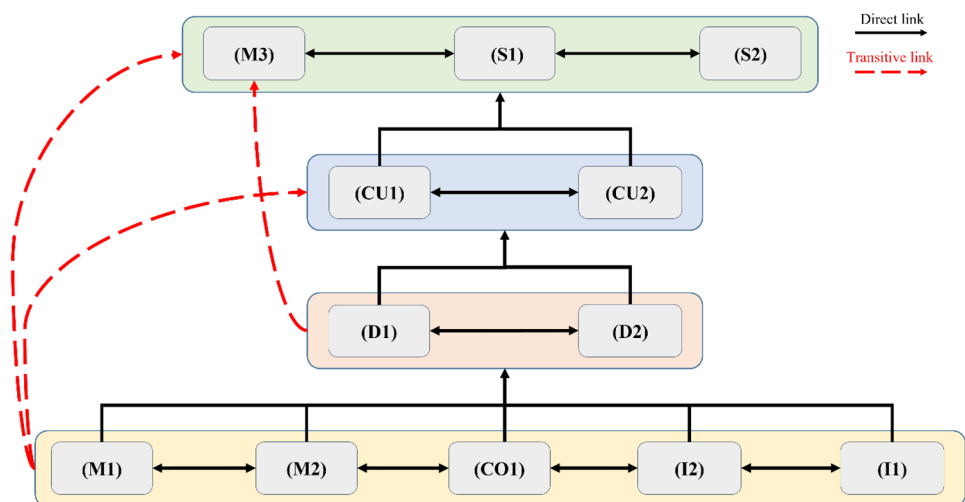**Fig. 3** TISM model for the quantitative factors of the RSC characteristics

Table 10 Direct influence matrix

	M1	M2	M3	I1	I2	CO1	S1	S2	D1	D2	CU1	CU2	Sum
M1	0	3	3	3	3	3	1	1	2	2	1	1	22
M2	1	0	1	1	1	1	1	1	2	2	1	1	22
M3	0	0	0	0	0	0	1	1	0	0	0	0	6
I1	3	3	2	0	3	2	1	1	3	2	1	1	24
I2	3	3	2	3	0	2	1	1	3	2	1	1	24
CO1	3	3	3	2	2	0	1	1	2	1	1	1	24
S1	0	0	2	0	0	0	0	3	0	0	0	0	5
S2	0	0	2	0	0	0	3	0	0	0	0	0	5
D1	0	0	1	0	0	0	0	0	0	3	1	1	6
D2	0	0	1	0	0	0	0	0	3	0	1	1	6
CU1	0	0	1	0	0	0	1	1	0	0	0	3	6
CU2	0	0	1	0	0	0	1	1	0	0	3	0	6
Sum	12	12	21	11	11	10	17	17	13	12	10	10	

indirect classifications according to the driving power and the dependency levels, M1, M2, I1, I2, and CO1 are independent factors, while S1, S2, and M3 are dependent factors.

The reconfigurability of supply chains can be related to two main structural and functional aspects. The structural aspect consists in changing the structure of the supply chain related to its design nature. On the other hand, the functional aspect is related to value creation aiming at improving the supply chain functions (purchasing, storage, flow management, etc.). Indeed, M1, M2, I1, I2, and CO1 are factors related to the structural design changes of the supply chain. Thus, modularity, integrability, and convertibility are characteristics that affect the components of the supply chain: the nodes, which represent suppliers, factories, distribution centers, etc., and the connections that designate the information and physical flows linking the nodes. These elements (nodes and connections) form the structural design of the supply chain. Figure 10 shows the interactions between the reconfigurability characteristics based on their evaluation factors.

5 Managerial and practical implications

The aim of this study is to identify and analyze the quantitative factors considered to evaluate the reconfigurability in supply chains. This analysis allows managers and decision-makers to know the most important factors in both the evaluation and implementation of reconfigurability. Indeed, these factors were identified, in the literature, according to the six characteristics of reconfigurability (modularity, integrability, convertibility, diagnosability, scalability, and customization). They also allow successfully implementing a RSC.

The factor analysis helped prioritize and classify the quantitative factors and consequently the reconfigurability characteristics. Indeed, the number of modules, the number of intra- and inter-module interactions, the number of nodes, and the number of connections between them as well as the supply chain redundancy represent the independent factors that influence the other factors. These factors show the importance of modularity, integrability, and convertibility

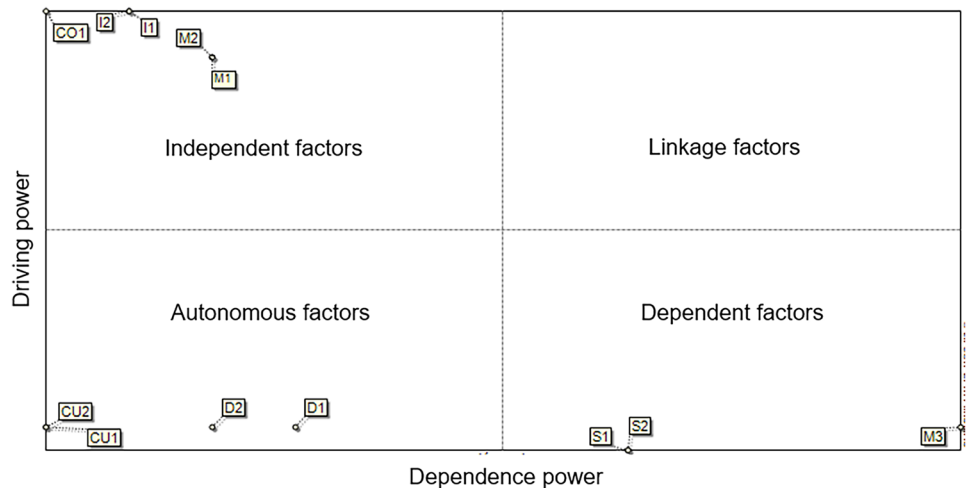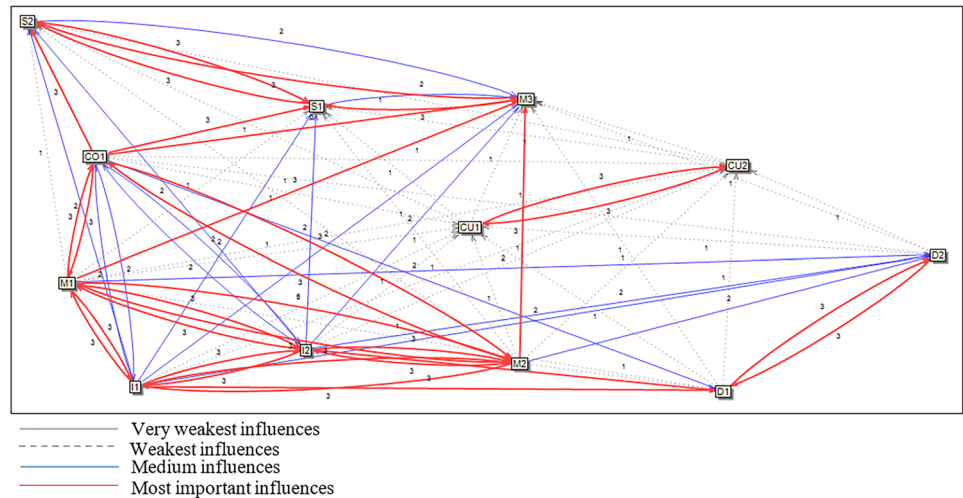**Fig. 4** Direct influence/dependence map

Fig. 5 Graph representing direct influence

in designing a RSC. These characteristics mainly impact the structural change of the supply chain. Indeed, improving the supply chain degree of reconfigurability requires modular design, reducing the degree of complexity, which depends on the number of nodes and connections, and increasing the redundancy of the supply chain. On the other hand, the supply chain visibility, related to the quantity and quality of the information shared between all the actors of the chain, and the detection time depend highly on the supply chain structure. Indeed, the less complex the supply chain is, the higher the visibility and the faster the detection time of failures will be. In addition, factors related to customization (response time and number of customized functions) depend on the supply chain structure. Thus, the modular design must be oriented towards mass customization. Finally, lead time,

latency, and throughput capacity are factors influenced by other factors and do not influence other factors. This classification allows understanding the impact of each factor on the evaluation of the supply chain reconfigurability and how to improve its degree through structural and functional changes.

The objective of our approach is to perform a detailed and methodological analysis of the reconfigurability characteristics and their identified quantitative factors. This analysis allows knowing the impact of each factor related to each characteristic on supply chain reconfigurability. This theoretical approach offers practical implications for managers and decision-makers in implementing a reconfigurable supply chain or improving reconfigurability. As an example, the results of our approach show that modularity and integrability allow reconfiguring the supply chain structure by decomposing the supply chain activities into a set of independent modules and reducing its structural complexity. In this example, we show managers that by implementing a

Table 11 Driving and dependency power values of the indirect influence matrix

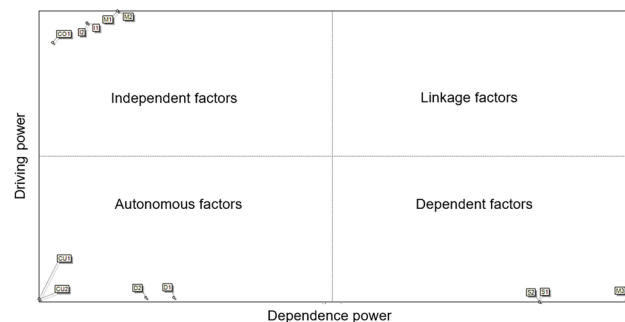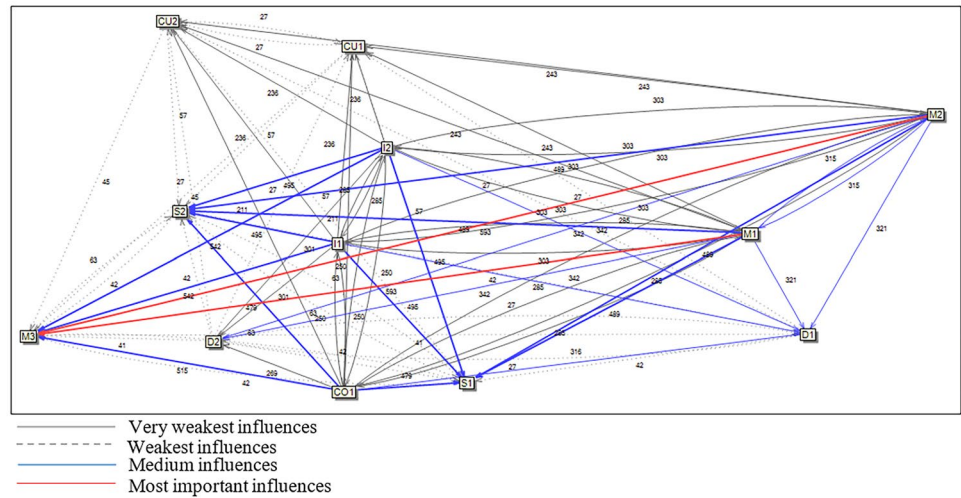|	Row total	Column total
M1	4214	1494
M2	4214	1494
M3	162	3077
I1	3772	1292
I2	4046	1399
CO1	4046	1399
S1	206	1669
S2	206	1582
D1	141	2807
D2	141	2807
CU1	186	1250
CU2	186	1250
	156	156

Fig. 6 Indirect influence/dependence map

Fig. 7 The graph representing indirect influence

modular supply chain, they can also improve their ability to easily and quickly integrate new entities.

Our approach allows managers to know what the company should focus on in its reconfiguration process according to its objectives. The interactions identified between the factors allow facilitating and improving the reconfiguration process by identifying the factors that change the supply chain functions and those changing the supply chain structure. The aim of this paper is to guide managers to best practices to ensure the improvement of the supply chain

reconfigurability through modularity, integrability, convertibility, diagnosability, scalability, and customization. In our previous works, we have proposed a model to evaluate the supply chain reconfigurability; nevertheless, these works explore the characteristics independently. For this reason, this paper provides an effective tool for managers to use best practices to ensure reconfigurability through its six characteristics while integrating the interactions between them to optimize their reconfiguration process.
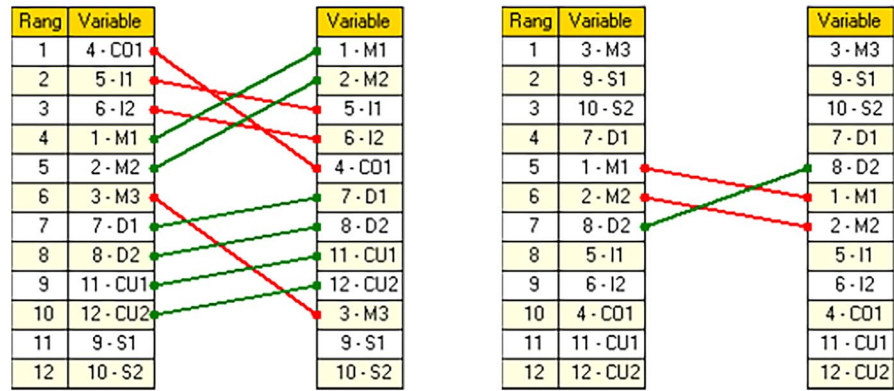
Table 12 Numerical factor weights of direct influences/dependencies

Factors	Direct influence	Factors	Direct dependency
CO1	1538	M3	1346
I1	1538	S1	1089
I2	1538	S2	1089
M1	1410	D1	833
M2	1410	M1	769
M3	384	M2	769
D1	384	D2	769
D2	384	I1	705
CU1	384	I2	705
CU2	384	CO1	641
S1	320	CU1	641
S2	320	CU2	641

Table 13 Numerical factor weights for indirect influences/dependencies

Factors	Indirect influence	Factors	Indirect dependency
M1	1958	M3	1429
M2	1958	S1	1304
I1	1880	S2	1304
I2	1880	D1	775
CO1	1752	D2	735
D1	95	M1	694
D2	95	M2	694
CU1	86	I1	650
CU2	86	I2	650
M3	75	CO1	600
S1	65	CU1	580
S2	65	CU2	580

Fig. 8 Factor classification

a. Classification of factors according to their influences

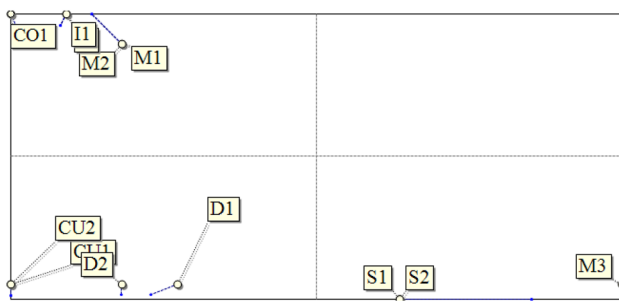**b.** Classification of factors according to their dependencies

6 Conclusion

Supply chain reconfiguration has recently become a crucial strategy to cope with disruptions and adapt to new market needs. The success of the reconfiguration strategy depends on ensuring its six characteristics (modularity, integrability, convertibility, diagnosability, scalability, and customization) that reduce the reconfiguration effort.

In this paper, the quantitative factors enabling to evaluate the degree of reconfigurability were identified from the literature and analyzed using the TISM approach and the MICMAC analysis. The influence of the identified factors on each other was studied to prioritize them. In fact, twelve factors related to the six previously mentioned characteristics were examined. Their influence was shown using a questionnaire that allowed constructing the influence matrix of the TISM approach. Based on the results obtained by the latter, the factors were classified into 4 levels according to their influences. Indeed, the number of modules, the number of intra- and inter-module interactions, the number of nodes, and the number of connections between them and the supply chain redundancy are the factors that influence other factors, but they are not influenced by them. This prioritization of factors was verified and validated by the MICMAC analysis through direct and indirect classifications of influences between factors. On the other hand, by interpreting these results, the characteristics were classified into two aspects (structural and functional). Modularity, integrability, and convertibility are related to the structural aspect, i.e., they allow changing essentially the design structure of the supply chain. However, the functional aspect of the RSC depends mainly on diagnosability, scalability, and customization.

These two identified dimensions are applicable to any type of supply chain because the identified factors can be related to all supply chains whatever their sector of activity, their type, their structures, etc. Indeed, ensuring modularity, integrability, and convertibility requires respectively the

Fig. 9 The direct/indirect displacement map

Table 14 Classification of factors according to their dependencies on other factors

	Dependent factors	Independent factors
Direct classification	M3, S1, S2	M1, M2, I1, I2, CO1
Indirect classification	M3, S1, S2	M1, M2, I1, I2, CO1
Intersection	M3, S1, S2	M1, M2, I1, I2, CO1

Fig. 10 Representation of the relationships between the characteristics of supply chain reconfigurability

decomposition of the supply chain into a set of independent modules, reducing the structural complexity of the supply chain while ensuring redundant entities. These characteristics are generic and can be guaranteed in all supply chains to reconfigure their structures, as they do not depend on the type of activity.

The same for diagnosability, scalability, and customization, which are guaranteed respectively by improving the visibility of the supply chain information, increasing the throughput of products and orders realized in the supply chain, and increasing its customizable functions. These suggestions can be applied in all supply chains whatever their sectors of activity, which contributes to the reconfiguration of the supply chain functions.

The proposed model allowed classifying the quantitative factors evaluating the six reconfigurability characteristics according to their influence on each other. However, the attribution of weights to each characteristic in the evaluation of the degree of reconfigurability cannot be assigned using our model. Indeed, the importance of the characteristics changes as a function of the sector, the market disruptions, the customers' requirements, etc. In order to apply the results of our approach, we propose to study the example discussed in [20]. This case study dealt with reconfigurability in a pellet stove distribution company; thus, the results of our approach enable to improve this case study by integrating the identified interactions in order to optimize the reconfiguration processes. On the other hand, we propose to apply our results in companies that have found difficulties in dealing with the effects of COVID-19 on the market (transport companies, hypermarkets, etc.).

The proposed approach has two main limitations. First, the survey conducted to identify the interactions between the factors related to the six characteristics must be extended to include a larger number of experts. Second, this paper addresses the six characteristics of supply chain reconfigurability to improve its ability to adapt to new changes and cope with market disruptions. Nevertheless, it will be important to integrate other concepts that also address the improvement of supply chain performance in a changeable and uncertain environment, such as resilience, agility, and viability. In future work, we will focus on the importance of each characteristic in the reconfigurability assessment process by taking into consideration their influence on each other.

Data availability The authors have no data or supplementary material to declare but the data will be made available to reviewers if necessary. The authors confirm that the data supporting the findings of this study are available in the article.

Code availability No code to declare.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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