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Strategy using modularity tools to operationalize mass customization in manufacturing small and medium-sized enterprises

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ABSTRACT

With the rise of technology, increasing competitiveness, market globalization and the fourth industrial revolution, companies are forced to rethink the way they do business to create or maintain a competitive advantage. Consumers, who are increasingly informed, demanding and concerned about sustainable development, are forcing companies to adapt to their needs to respond adequately to personalized demand. Small and medium-sized enterprises (SMEs) in the manufacturing sector must adjust to this new context. The move towards mass customization is one way of meeting customer requirements. However, no strategy for making this shift currently exists in the literature. The aim of this article is to present a strategy for operationalizing mass customization using modular tools. Action research is used to test the proposed strategy. The paper proposes 4 transformation axes to migrate towards mass customization: Modular product design, Modular process design, Technology use, Collaboration network. This article also highlights the need to tackle modular product design first to migrate to mass customization, by proposing a 3-stage strategy: modular product architecture, standardization of interfaces and definition of configuration rules. A case study is used to test the proposed strategy.

1. Introduction

The technological evolution and the implementation of new production processes in recent years have forced SMEs in the industrial sector to transform significantly (Ingaldi and Ulewicz, 2020). With the emergence of the fourth industrial revolution, the increasing demands of customers, the growing importance of sustainable development and labor shortages, companies are being forced to rethink the way they do business in order to remain competitive and sustainable (Caggiano et al., 2015; Abdulnour et al., 2022; Cotrino et al., 2020; Sonego et al., 2018; Park et al., 2016). Small and medium-sized enterprises (SMEs) in the manufacturing sector must adapt to personalized customer demands (Abdulnour et al., 2022). SMEs also need to adapt to demonstrate more sustainable management across all their activities (Park et al., 2016). This volatile, uncertain, complex, and ambiguous (VUCA) environment imposes manufacturing agility and drives SMEs to migrate to mass customization to increase their competitiveness, meet customer requirements and agility (Caggiano et al., 2015; Genest and Gamache, 2020; Cannas et al., 2022; Arnaud, 2019).

An exploratory literature search enables us to target the gaps in the literature. Indeed, in their research, Abdulnour, Baril, Abdulnour and Gamache (Abdulnour et al., 2022), put forward that Industry 4.0, the migration to mass customization and the digital shift make it possible to improve productivity, ensure economic growth and the sustainable development of an SME in the manufacturing sector. However, they point out that SMEs do not have sufficient resources at their disposal to undertake this shift (Abdulnour et al., 2022). Also, in their research, Bouchard, Gamache and Abdulnour (Bouchard et al., 2023) put forward, through a literature review, the need to prioritize and explore the factors to implement mass customization in the absence of a formal strategy. Thus, in the light of this exploratory research, a gap on how to operationalize mass customization, the tools to be put in place to achieve it and the necessary sequencing emerges in the literature. This absence forces us to question how mass customization can be implemented, what role agility and product modularization play in this shift, and how SMEs can become more connected and competitive. Mass customization is defined by Cohen and Pine Li (Cohen and Pine Li, 2007) as a low-cost, efficient production able to offer a high volume customized product. Invented in 1989 by Davis (Davis, 1989), it aims to offer a customized product that meets the customer's requirements, with similar reaction time and production efficiency to mass production (Wang and Mo, 2020).

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In this regard, to the best of our knowledge, no formal strategy for operationalizing mass customization and increasing the agility of an SME currently exists (Bouchard et al., 2023). In this context, it is crucial to develop such a strategy considering the tools, technologies, and principles of Industry 4.0.

This article establishes and develops the tools that must be implemented to facilitate the implementation of a strategy to operationalize the shift of an SME in the manufacturing sector toward customized mass production. This study proposes the identification, development, and analysis of the tools to be used, as well as their application context, with the aim of filling a gap in the literature. The results of this study will make an important contribution by proposing existing and future tools for operationalizing product modularization in SMEs in the manufacturing sector.

The remainder of the article is organized as follows. Section 2 presents a literature review. Section 3 explains the research methodology used. Section 4 details the results of the action research. Section 5 contains a discussion of the results. The final section is a conclusion on the tools for sequencing the strategy. This strategy will be developed and tested through an action-research case study of a small to medium-sized manufacturer of school and commercial buses. This SME was chosen for the case study because it faces a specific context favoring the implementation of mass customization due to norms and legal standards applicable in this sector of activity.

2. Literature review

2.1. Mass customization

In their research, Bouchard, Gamache and Abdulnour (Bouchard et al., 2023) highlight the growing need for companies to migrate to mass customization, as they face dynamic demand and high customer expectations. Indeed, customers show a growing interest in receiving personalized sustainable products or services (Park et al., 2016; Pech and Vrchota, 2022). This migration to mass customization is forcing companies to adapt their production systems to be more flexible (Pizoń and Gola, 2023).

Customization is intended to allow customers to define a product according to their tastes and needs (Martínez-Olvera, 2022). However, mass customization is intended to produce customizes products at mass production costs, as can be seen in Fig. 1 (Saniuk et al., 2020; Forza and Salvador, 2006).

Mass customization is distinguished by the use of modules designed by the manufacturer and offered as options to customers (Martínez-Olvera, 2022). In addition, Industry 4.0 is extremely concerned with rapidly, efficiently and cost-effectively responding to customized product demand (Martínez-Olvera, 2022; Dziurzanski et al., 2018). Mass customization is therefore a potential solution (Martínez-Olvera, 2022). Fig. 2 depicts the number of articles with mass customization as a keyword in recent years. As illustrated in Fig. 2, this topic has been increasingly addressed in the scientific literature since the emergence of Industry 4.0.

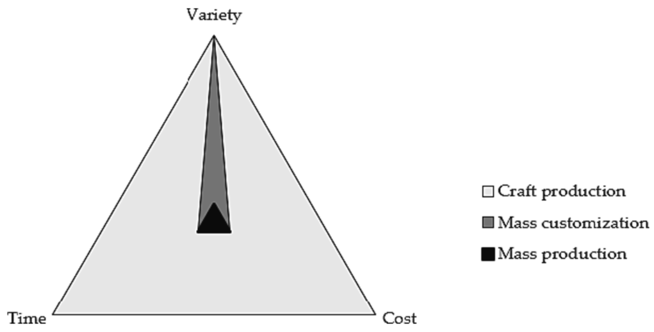


Fig. 1. Relationship between types of production and variety offered adapted from Forza and Salvador (Forza and Salvador, 2006).

Along with digitization and the implementation of flexible production systems, mass customization allows companies to get closer to their customers by strengthening their brand, improving product knowledge and staying ahead of market changes and evolution (Pech and Vrchota, 2022). Mass customization therefore allows companies to create and maintain a competitive advantage (Pech and Vrchota, 2022).

Although the benefits of mass customization are known, how to operationalize it within a manufacturing SME is still a topic of research. The transition to mass customization requires adaptations in different areas of a company, such as product architecture, manufacturing, and technological processes, as well as in the distribution network (Huang and Kusiak, 1998; Su et al., 2005; Piller, 2010). The research also seeks to identify success factors that facilitate the implementation of the proposed tools. In their research, Suzic and Forza (Suzic and Forza, 2021) discuss guidelines for implementing mass customization.

[1] Development of the product platform
[2] Product modularity
[3] IT-based product configuration
[4] Parts standardization
[5] Group technology
[6] Process modularity
[7] Simultaneous product-process-supply chain integration

These characteristics have been grouped under four business transformation guidelines: modular product design, modular process design, technology use and collaborative network. Fig. 3 illustrates the four transformation axes and how the guidelines of Suzic and Forza (Suzic and Forza, 2021) have been grouped together.

The relationship between modular product design and mass customization facilitates a better integration of the other axes and makes it possible to achieve and maintain competitive performance (Aeknarajindawat and Chancharoen, 2019; Zhang et al., 2019). Research suggests that modular product design is the initial transformation axis, i.e., the starting point for successfully implementing mass customization (Aeknarajindawat and Chancharoen, 2019; Zhang et al., 2019; Tu et al., 2004; Peng et al., 2011; Zhang et al., 2014; Fixson and Park, 2008; Seyoum, 2021; Sturgeon, 2002; Wang et al., 2014; Yan et al., 2022). Fig. 4 illustrates the relationship between mass customization, modular product design, quality integration and competitive performance (Zhang et al., 2019).

Analyzing this first axis of transformation—modular product design—makes it possible to target the tools to be developed for SMEs in the manufacturing sector to begin implementing mass customization. By looking first at modular product design, this article looks at how to implement mass customization, the role of agility and product modularization in this shift, and how SMEs can become more connected and competitive.

2.2. Product modularity

Modular product design means modular design (Tu et al., 2004). Modular design is a design method that makes it possible to divide a complex system into smaller modules (Tu et al., 2004). Modular architecture, shown in Fig. 5, helps to illustrate the basic principle of modular design.

A module is a functional group that contributes to a given function of the final product (Bonvoisin et al., 2016). Therefore, modular products are made up of modules. Modular product design is considered the act of designing a product that is composed of modules (Bonvoisin et al., 2016). Fig. 6 details the modular product design approach. First, the different modules are designed, then the modules are identified and finally, the modules are used to design the product.

With modular products, the creation process can be standardized

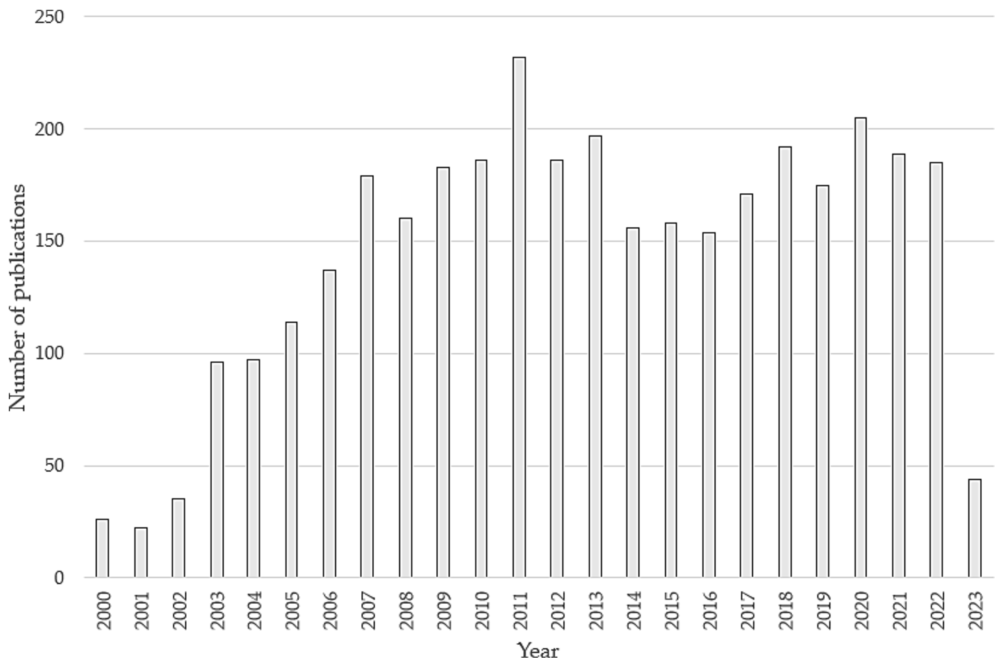


Fig. 2. Number of publications per year related to mass customization.

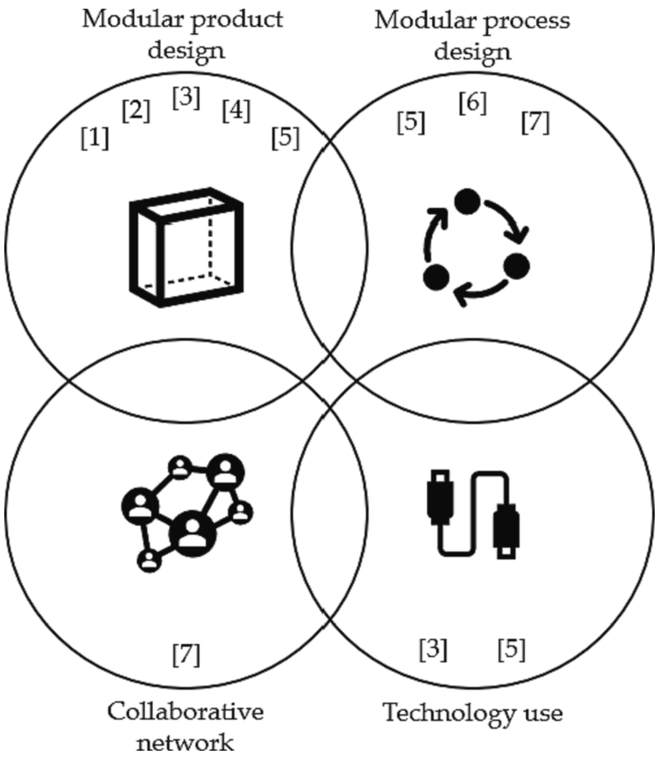


Fig. 3. Four transformation axes for mass customization.

since it limits part variability, without reducing the range of choices offered to the customer (Koppenhagen and Held, 2021). Indeed, modular design seeks to increase the commonality between products (Pakkanen et al., 2022). Modularity also brings benefits in terms of sustainable product design (Sonego et al., 2018). Indeed, modularity optimizes resources, reduces inventory, increases collaboration between companies, facilitates maintenance, and increases the company's flexibility (Sonego et al., 2018). These benefits make it possible to meet customers' requirements in terms of sustainable development.

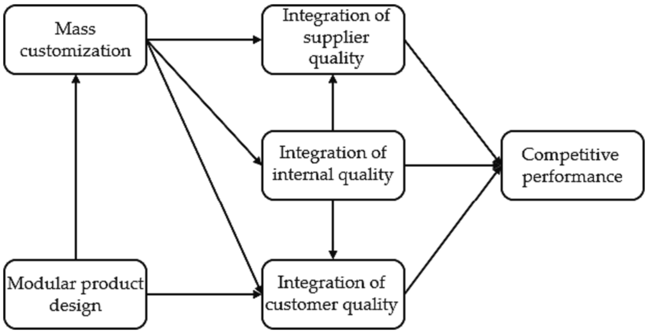


Fig. 4. Relationship between mass customization, modular product design, quality integration and competitive performance adapted from Zhang, Guo, Huo, Zhao and Huang (Zhang et al., 2019).

In addition, a modular product design offers many more benefits, which extend to several sectors of a manufacturing company (Pakkanen et al., 2022). Table 1 details the sectors that might benefit from modular product design and the associated benefits (Pakkanen et al., 2022).

Modular product design must be properly implemented to provide its potential benefits. Modular design first seeks to develop a modular architecture based on the company's range of products by breaking down products into modules (Pakkanen et al., 2022; Cusumano, 2008). Then, the independent components or subassemblies are isolated in new modules (Pakkanen et al., 2022; Baldwin and Clark, 2000). The interfaces are then standardized to ensure the module variants are interchangeable (Pakkanen et al., 2022; Parslov and Mortensen, 2015). Lastly, configuration rules and product variant constraints are set up in accordance with the products offered (Pakkanen et al., 2022; Pakkanen et al., 2016). In addition, products composed of compatible modules are offered to customers (Pakkanen et al., 2022; Bongulielmi et al., 2001). The literature review contains tools for these three steps:

1. Product breakdown according to a modular architecture
2. Interface standardization
3. Definition of configuration rules

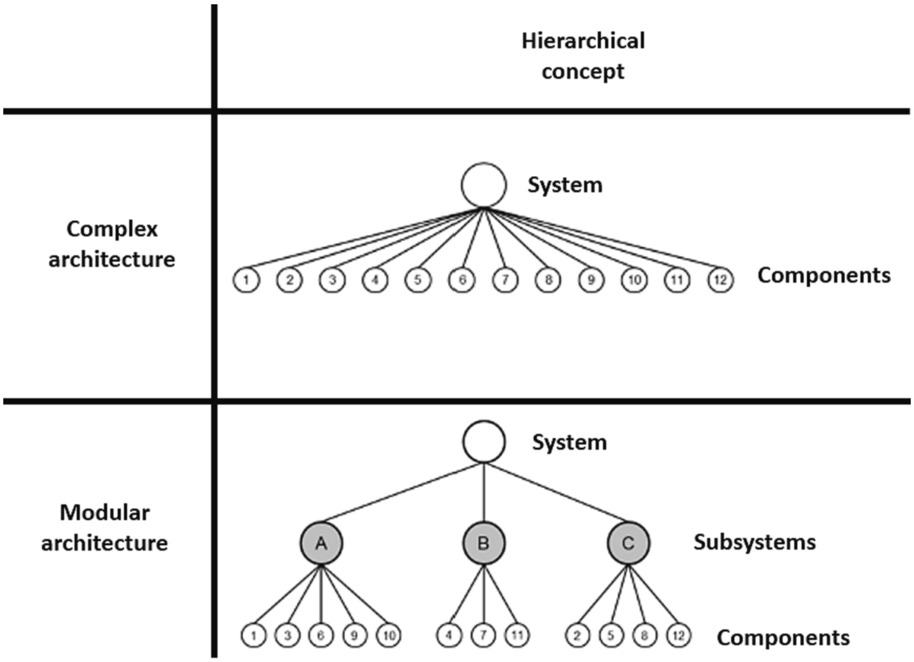


Fig. 5. Structural tree from a general systems perspective adapted from Koppenhagen and Held (Koppenhagen and Held, 2021).

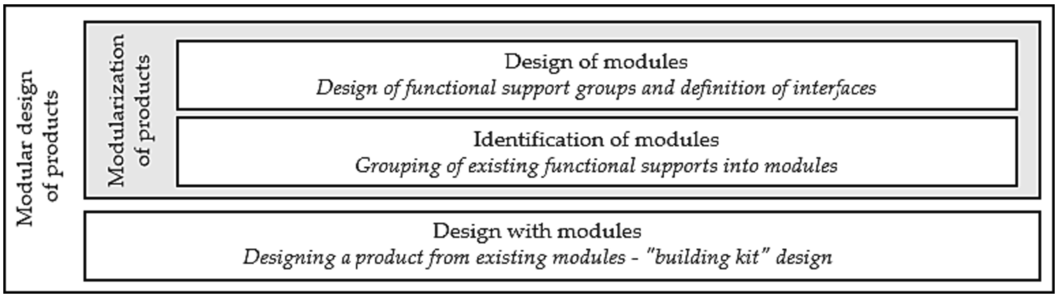


Fig. 6. Modular approach to product design (Bonvoisin et al., 2016).

2.2.1. *Tools and integration: Product breakdown according to a modular architecture*

Product breakdown according to a modular architecture consists in grouping components with a high degree of interaction (Yu et al., 2007; Kulkarni et al., 2018, 2018; Sosa et al., 2007). Modules are formed by grouping these components. The “Design Structure Matrix” (DSM) or “Dependency Structure Matrix” (DSM) make it possible to represent the relations between the systems and the components in order to target the most judicious way to cut the product (Sharman and Yassine, 2004). The DSM is derived from a linkage graph between the components of a product. Each component represents the title of a column and a row of the DSM. The interactions between the components are represented by an “X” in the DSM. The diagonal is blacked out because it has no particular meaning since it represents the relationship between the component itself (Sharman and Yassine, 2004). Fig. 7 shows a simple product without a module.

The left part of Fig. 7 illustrates the relationship between the components. The middle part of Fig. 7 illustrates the DSM. The right part of Fig. 7 illustrates how to cut the product, i.e., without using modules in this case. Fig. 8 illustrates a simple product with the creation of two modules.

The left part of Fig. 8 illustrates the relationship between the components. The central part of Fig. 8 illustrates the DSM. The right part of Fig. 8 illustrates how to cut the product, i.e., using two modules in this case. Fig. 9 illustrates another example, with a product from which three modules can be created.

The left part of Fig. 9 illustrates the relationship between the components. The central part of Fig. 9 illustrates the DSM. The right part of Fig. 9 illustrates how to cut the product, i.e., using three modules in this case. Moreover, when the DSM is initially created according to the component relationships, the columns and rows can be reorganized to favour the creation of modules (Yu et al., 2007; Kulkarni et al., 2018, 2018; Sosa et al., 2007). Fig. 10 shows an example of a DSM from the original design.

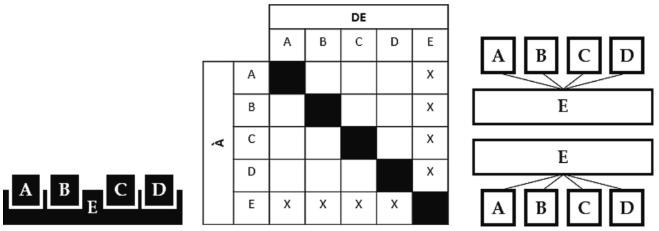
After making the original matrix, reorganization makes better regrouping possible, as can be seen in Fig. 11.

Moving several columns and rows thus provides better clustering. As a last step, the groupings can be adjusted to include the largest number of components, as can be seen in Fig. 12, following an alternative grouping.

Product slicing can be used to group components to form modules based on component interactions. Modules that are considered generic elements that do not affect customer needs are an opportunity for standardization, while modules that can vary according to customer needs create challenges for standardization. (Pakkanen et al., 2016; Juuti, 2008). Schematizing the product in hierarchical form makes it possible to understand the product’s configuration constraints (Pakkanen et al., 2016; Juuti, 2008). Separating standard modules, modules that can be configured according to customer needs, partially configurable modules and independent components makes it possible to

Table 1
Benefits of modular product design by sector (Pakkanen et al., 2022).

Sector	Benefits
Product development and product data management, product modularity	• Enhances overall understanding of the product and the effects generated by design decisions. Simplifies integration of new products due to modularization.
Service	• Favours redundancy in both components and maintenance.
Procurement of materials and components	• Achieves economies of scale. Improves visibility of supply needs.
Commissioning and approval	• Facilitates module verification due to separation.
Renewal, dismantling and reuse of components	• Extends product life cycle by encouraging the reuse of certain components.
Sales	• Increases information about the design available to existing team. Enhances offer preparation. Frees up time to develop better sales arguments to close deals.
Pre-assembly of predefined components and modules	• Increases the amount of pre-assembly that can be done upstream. Requires less quality control due to module repeatability.
Logistics	• Improves transport management due to module redundancy.
Production line assembly	• Lowers associated costs by outsourcing certain modules where possible.
Engineering	• Improves efficiency in revision and design management.



	A	B	C	D	E
A	■				X
B		■			X
C			■		X
D				■	X
E	X	X	X	X	■

Fig. 7. A simple product without a module adapted from Sharman and Yassine (Sharman and Yassine, 2004).

visually represent the product structure, as can be seen in Fig. 13 (Juuti, 2008).

This product structure makes it easier to understand a product's complexity and composition. This structure also serves to determine and standardize the interfaces between the different product components.

2.2.2. Tools and integration: Interface standardization

Standardizing and normalizing the interfaces between the components and modules of a modular architecture product allow for greater flexibility to better respond to changing customer demands (Doran and Hill, 2009; McAlinden et al., 1999; Sanchez, 2002; Ikeda and Nakagawa, 2001). As part of their research, Sanchez and Collins (Sanchez and Collins, 2001) described the development of a modular architecture product in two steps. The first step is decomposing the product according to the specific components constituting the structure of the product (Sanchez and Collins, 2001). The second step is specifying the interfaces to define the interactions between the functional components (Sanchez and Collins, 2001).

Furthermore, according to the work of Sanchez and Collins (Sanchez and Collins, 2001); for a product to be modular, the interfaces between the components must be specified and standardized in order to make product components interchangeable. These conditions make it possible to offer combinations of the different modules to better meet customer requirements (Sanchez and Collins, 2001).

To implement and integrate interface standardization in a modular product design, an interface diagram can be used to visually understand the interactions between the modules and the components that compose the product (Bruun et al., 2014). This tool is like a visual representation of a product architecture model, with the aim of making it possible to integrate a modular product's functional subsystems. The purpose of the interface diagram is to support the decomposition of a modular product composed of several subsystems (Bruun et al., 2014). Bruun, Mortensen and Harlou (Bruun et al., 2014) tested the usefulness of this diagram in a development project in a manufacturing context. At the end of this implementation, they concluded that the interface diagram reduced engineering delays and decreased non-value-added actions by minimizing rework in design and manufacturing. (Bruun et al., 2014).

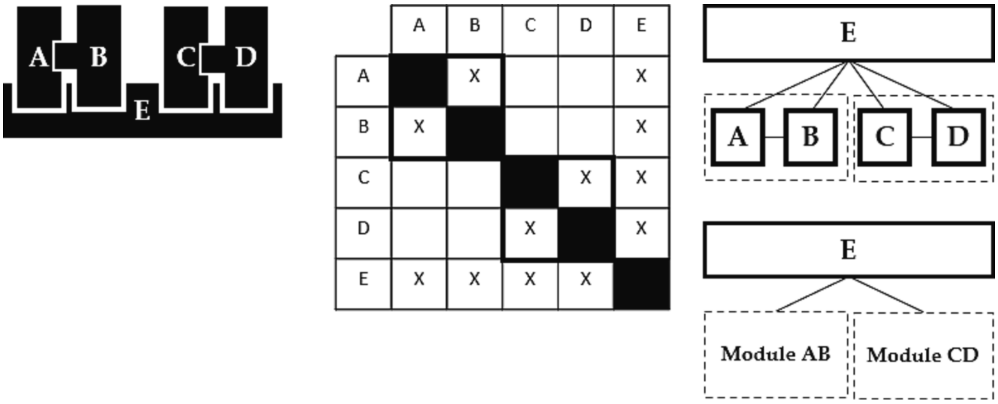
The interface diagram illustrates the product breakdown by components and modules. Each component's name, affiliation to a primary system and to a secondary and tertiary system if necessary, and the quantity present in the product are specified. In addition, the nature of the interface between each component is identified. Fig. 14 shows the symbolic representation of a generic interface diagram (Bruun et al., 2014).

Since the nature of the interface between each component is represented visually on the interface diagram, standardization can be performed at the interface level to ensure uniformity.

2.2.3. Tools and integration: Defining configuration rules

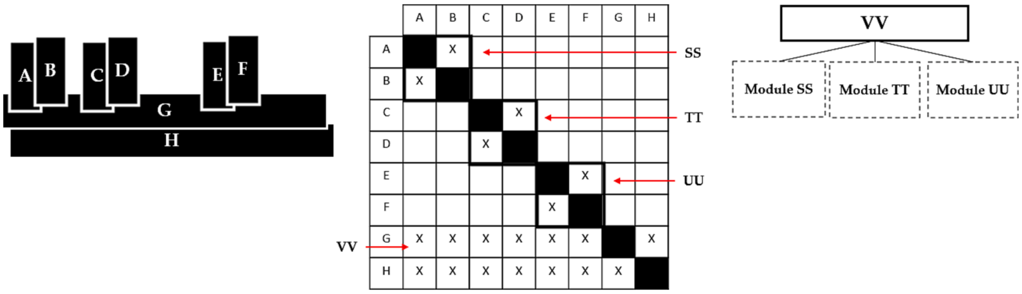
Setting up configuration rules is the last step in implementing modular product design. Product configuration makes it possible to select different existing modules based on previously established configuration rules to assemble a product (Song et al., 2021; Fogliatto et al., 2012; Salvador, 2007; Hvam et al., 2008).

To establish a product's configuration rules, companies must know what they want to offer on the market (Forza and Salvador, 2008).



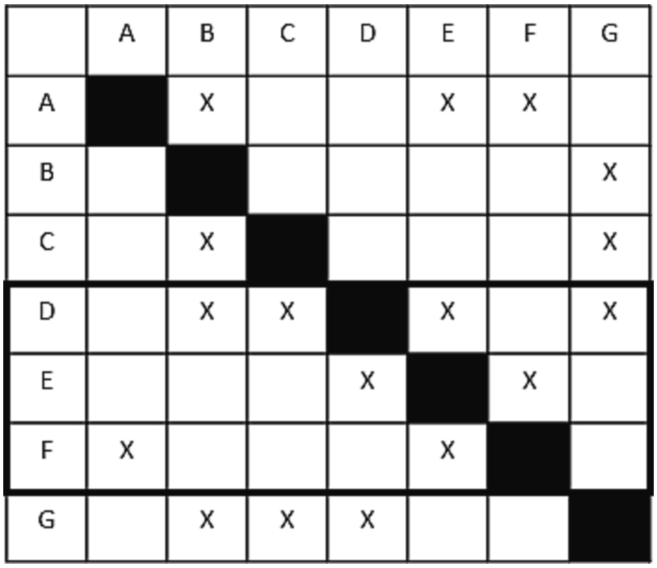
	A	B	C	D	E
A	■	X			X
B	X	■			X
C			■	X	X
D			X	■	X
E	X	X	X	X	■

Fig. 8. A simple product with two modules adapted from Sharman and Yassine (Sharman and Yassine, 2004).



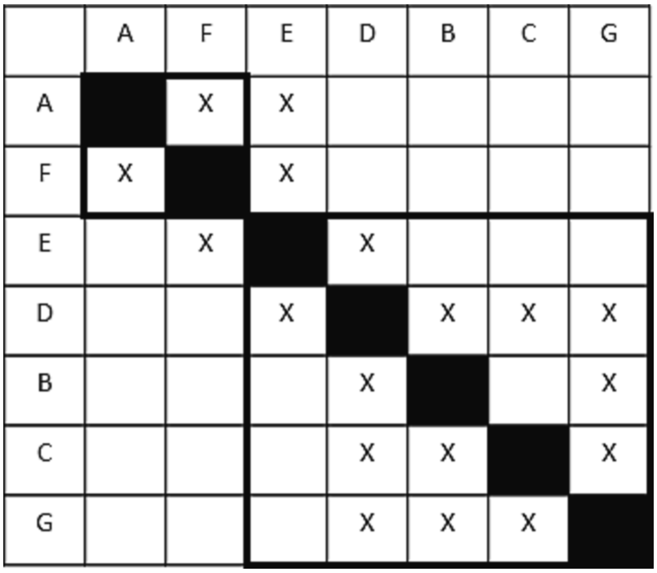
	A	B	C	D	E	F	G	H
A	■	X						
B	X	■						
C			■	X				
D			X	■				
E					■	X		
F					X	■		
G	X	X	X	X	X	X	■	X
H	X	X	X	X	X	X	X	■

Fig. 9. A product with three modules adapted from Sharman and Yassine (Sharman and Yassine, 2004).



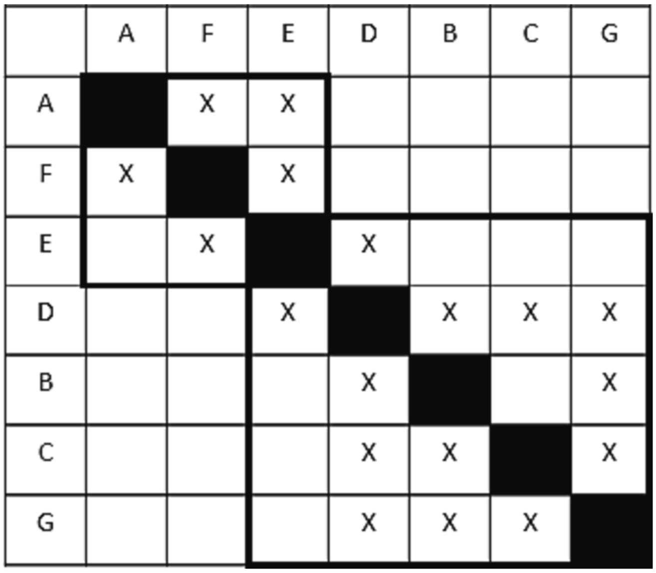
	A	B	C	D	E	F	G
A	■	X			X	X	
B		■					X
C		X	■				X
D		X	X	■	X		X
E				X	■	X	
F	X				X	■	
G		X	X	X			■

Fig. 10. Original DSM adapted from Sharman and Yassine (Sharman and Yassine, 2004).



	A	F	E	D	B	C	G
A	■	X	X				
F	X	■	X				
E		X	■	X			
D			X	■	X	X	X
B				X	■		X
C				X	X	■	X
G				X	X	X	■

Fig. 11. Clustered DSM adapted from Sharman and Yassine (Sharman and Yassine, 2004).



	A	F	E	D	B	C	G
A	■	X	X				
F	X	■	X				
E		X	■	X			
D			X	■	X	X	X
B				X	■		X
C				X	X	■	X
G				X	X	X	■

Fig. 12. Alternative grouping adapted from Sharman and Yassine (Sharman and Yassine, 2004).

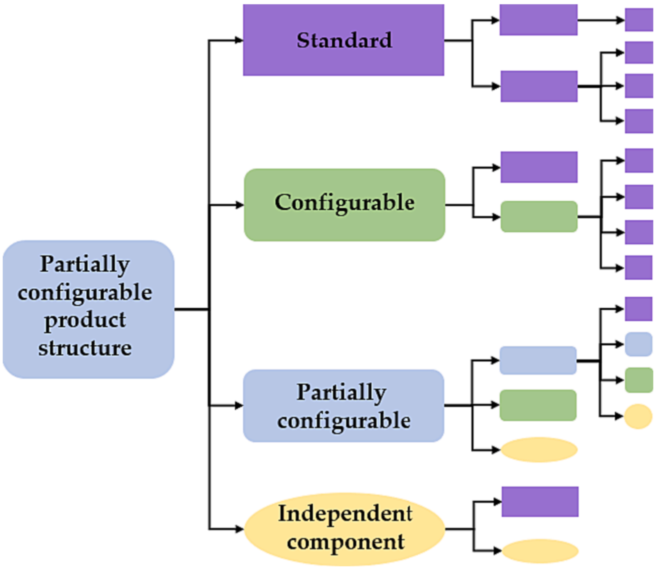


Fig. 13. Partially configurable product structure adapted from Juuti (Juuti, 2008).

Defining a product offer that satisfies customer demand makes it easier to set up configuration tags (Forza and Salvador, 2008). Potential product variants must not require redesign. Variants are expected and therefore pre-designed. Product feasibility should be considered at the design stage, rather than the configuration stage (Forza and Salvador,

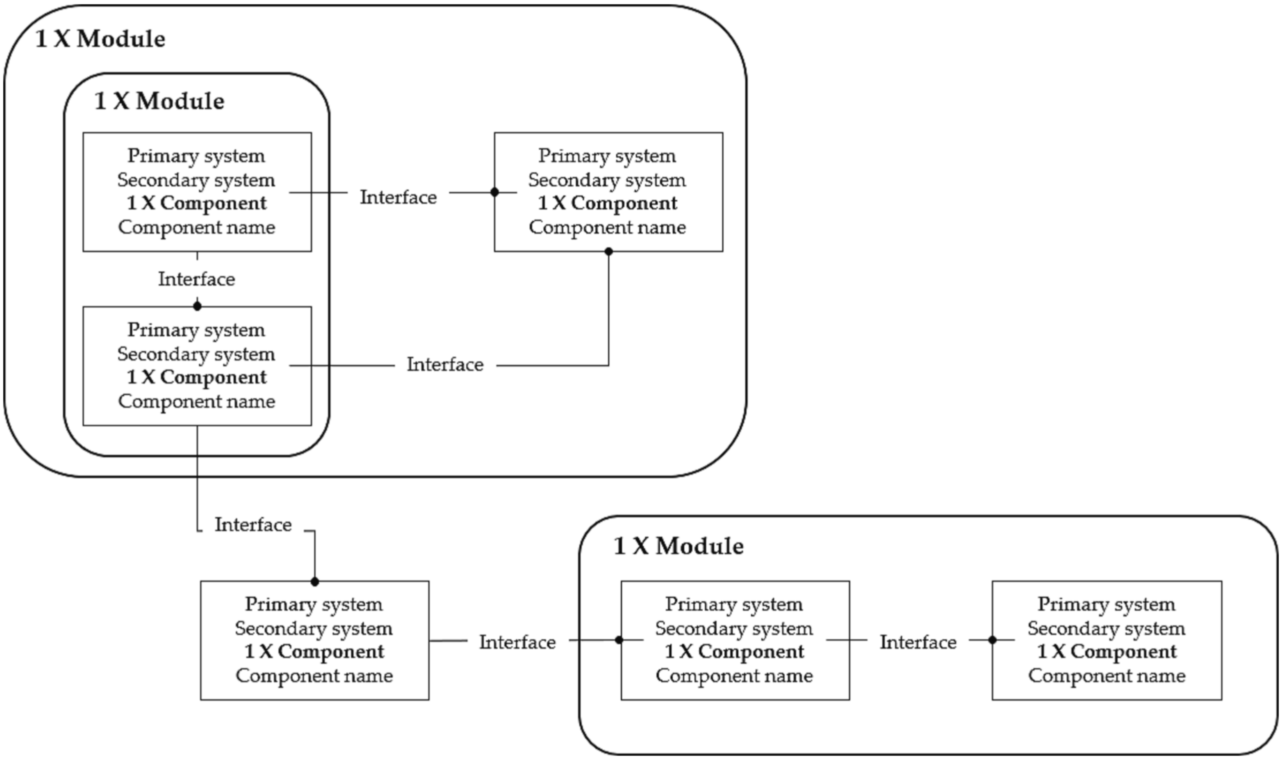


Fig. 14. Symbolic representation of an interface diagram adapted from Bruun, Mortensen and Harlou (Bruun et al., 2014).

2008). By respecting these constraints, defining configuration rules creates a range of product possibilities, based on the possible variations of how components can be assembled. Configuration rules thus favour the efficiency and reactivity of companies offering a variety of products (Forza and Salvador, 2008).

Fig. 15 illustrates the factors to consider when establishing a product's configuration rules (Custódio et al., 2018).

Product characteristics are derived from the market needs for the product, i.e., the main categories that customers can select: power, capacity, motorization, etc. (Custódio et al., 2018). Product variability is the range of possibilities for each characteristic: different power options, different capacity options, different motorization options. Lastly, standards may impose restrictions on products, which may be directly linked to product characteristics (Custódio et al., 2018). Fig. 16 details an example of the characteristics, variability and possible restrictions on a specific product (Rasmussen et al., 2020).

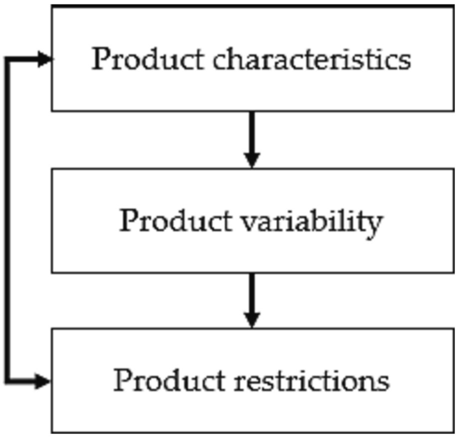


Fig. 15. Elements to consider in configuring a modular product adapted from Custódio, Roehe Vaccaro, Nunes, Vidor and Chiwiacowsky (Custódio et al., 2018).

In Fig. 16, the characteristic is the type of motorization, the variability is the different motorization choices available, and the restriction is a specific rule applied according to the province in which the product is used. Based on these factors, a model can be matched to a modular product that respects this configuration. Fig. 17 specifically focuses on module configuration.

In the same vein as Fig. 16, Fig. 17 presents a module configuration. Configuration rules specific to each model offered are used, serving to consider variability at the module level.

In short, the development of a strategy based on these different tools addresses the gap on how to implement mass customization through, initially, modular product design.

3. Research method

The research method is participatory action research (PAR), a qualitative research method. PAR makes it possible to integrate methods, techniques, documentation and characteristics related to a phenomenon under study (Leininger, 1985; Gillis and Jackson, 2002; MacDonald, 2012). This qualitative method seeks to describe and understand functioning rather than to predict and control it (MacDonald, 2012).

It combines both the creation of knowledge and the application of this knowledge in a practical context (Huang, 2010). It requires collaboration between research and practitioners in the field. Its aim is to create knowledge with a practical orientation (Huang, 2010). Action validates research. This article uses action research to test the proposed strategy. The choice of methodology was based on the validation criteria of action research. Table 2 describes the 7 essential criteria for validating the need to use action research as a research methodology (Huang, 2010; Morales, 2016; Kemmis and McTaggart, 1988).

On a more technical level, for this research, modular product design was implemented in an SME seeking to shift toward mass customization. The strategy was divided into three steps: product breakdown according

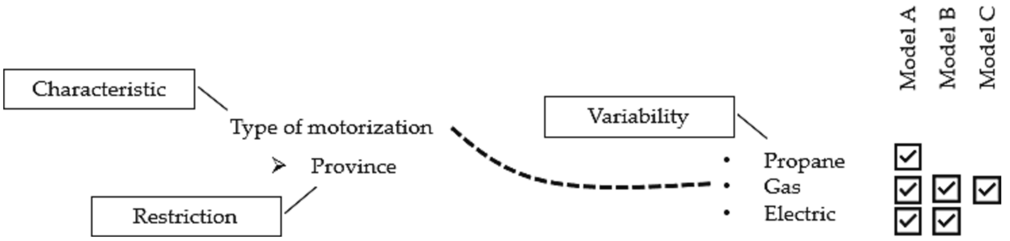


Fig. 16. Elements to consider when configuring a modular product adapted from Rasmussen, Hvam, Kristjansdottir and Mortensen (Rasmussen et al., 2020).

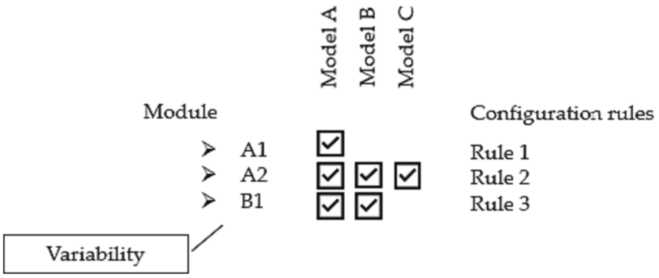


Fig. 17. Elements to consider when configuring a modular product adapted from Rasmussen, Hvam, Kristjansdottir and Mortensen (Rasmussen et al., 2020).

Table 2
Criteria for validating the quality of action research (Huang, 2010; Morales, 2016; Kemmis and McTaggart, 1988).

Criteria	Description
Collaborative participation	Importance of collaboration between the various players involved
Cyclical nature	Importance of the iterative process between research, action, observation, and validation
Practice transformation	The importance of making a tangible change in practice
Reflexivity	Importance of critical reflection on the process and results obtained
Knowledge production	Importance of generating theoretical and not just practical knowledge
Validity and reliability	Importance of the relevance and consistency of the results obtained
Ethics	The importance of demonstrating integrity and respecting the ethical rules applicable to each context

to a modular architecture, interface standardization and configuration rule definition. Each of the 3 steps and their sequence will be detailed in this article. Fig. 18 illustrates the three steps of the strategy to be validated in a manufacturing SME.

To implement the stages of the strategy proposed in Fig. 18, the Stage-Gate model was deployed. The stages of the stage-gate process presented by Karlström and Runeson (Karlström and Runeson, 2005) are detailed in Fig. 19: scoping, modeling, development, validation and implementation. The strategy is therefore supported by a rigorous validation process (Karlström and Runeson, 2005).

The following section details the deployment of the strategy, based step by step on the Stage-Gate model. In fact, the product breakdown according to a modular architecture, the standardization of interfaces and the definition of configuration rules is carried out in accordance with the tools available in the literature and those developed for the implementation of the strategy. The strategy was tested by means of a company case study, after which the sequence of implementation of the strategy steps was adapted and modified as required.

4. Presentation of the study

The PAR focuses on a product from a Quebec SME that manufactures school and commercial minibuses. Buses are subject to different standards from one city to another. A multidisciplinary team from different departments (product engineering, processes engineering, sales, IT, and logistics) performed the steps in the process. Once these steps were completed, a tested strategy for operationalizing the modular product design was proposed.

4.1. *Framing*

The first activity defining the primary characteristics of a basic vehicle. Certain components are essential to build a vehicle. This first step provides a first rough breakdown of the product. Fig. 20 shows the first draft of a primary breakdown in modular form.

This first draft serves as a base on which to build. Based on this breakdown, all the components in the following modules had to be identified: Electrical, Structure, Accessories, Lining, Mechanical.

A team comprising members of different departments performed the primary breakdown of the modules to ensure the entire product was captured. Several iterations were then produced to arrive at a complete end result. This stage also served to identify the components that would be part of the final modular breakdown. At the end of this framing stage, after several iterations, a total of 250 components and six main modules emerged as essential inclusions in the modular breakdown of the product. Table 3 details the main modules and the sub-modules present.

This modular breakdown allowed us to determine all the components

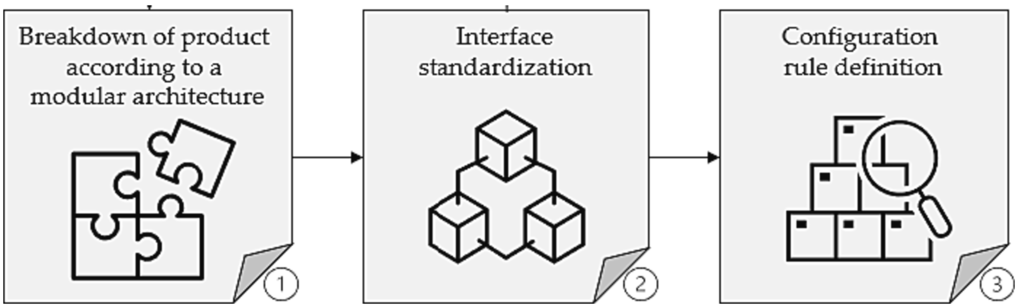


Fig. 18. Strategy to be validated to operationalize modular product design.

Fig. 19. Stages of the stage-gate process adapted from Karlström and Runeson (Karlström and Runeson, 2005).

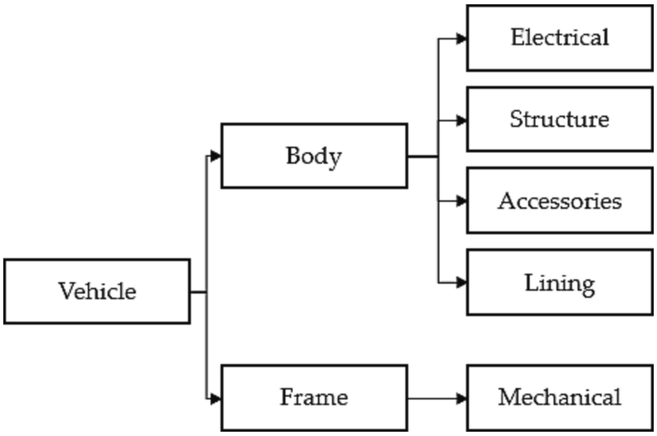


Fig. 20. Primary breakdown of the vehicle in modular form.

Table 3
Details of main modules, sub-modules, and components.

Main module	Number of sub-modules
Interior lining	4
Exterior lining	6
Frame	0
Body	7
Electrical	0
Air conditioning/heating	0

that were taken into consideration in the following steps. Indeed, the product was initially cut according to the principle of a complex architecture at only one level as described by Koppenhagen and Held (Koppenhagen and Held, 2021). Therefore, there were no modules and no hierarchy between the components.

4.2. Modelling

Once the framing stage was completed, the modelling took shape. The modelling step in the stage-gate process took what was done in the framing phase and prepared it for the development phase. This involved visually preparing the basic modular breakdown for the implementation of the modular tools. Several iterations were necessary to arrive at a result ready for the development phase.

Workshops allowed us to split the product according to a hierarchical modular architecture (Koppenhagen and Held, 2021). Once again made up of members from different departments, the team deconstructed products in a modular way using the strategy proposed by Koppenhagen and Held (Koppenhagen and Held, 2021). Fig. 21 illustrates the product hierarchical modular architecture.

Fig. 21 is based on Table 2 and includes all the components that were identified in the framing phase. For each module identified, the related components are listed below the product structure to simplify the overall structure.

4.3. Development

Furthermore, based on the DSM, the modules were decomposed using the matrix steps to ensure their viability. As an example, the method used for the “Main Structure” module will be detailed.

First, the components that could be found in the module are highlighted. Table 4 details the module component groups.

The seven components need to be grouped into different modules. However, understanding the interactions between the components is necessary to properly group them. Fig. 22 illustrates how the interface diagram can be used to understand component interactions.

Then, the DSM is used to visually represent the component interactions. The matrix shows that two groupings are formed naturally based on interactions. Fig. 23 and Fig. 24 illustrate the resulting module groupings.

The DSM shows that the ideal “Main Structure” formation is three modules that all contain a different number of components. Fig. 25 illustrates the interaction between the three modules that have been created.

This exercise must be performed when creating each module to ensure the modules are viable based on the interactions between the components. Thus, based on the hierarchical modular architecture, the modules within the product can be better detailed. Once the breakdown has been performed for the entire product, the interface diagram can be used to visually represent the product, its modules, its components, and its interactions. Using the interface diagram proposed by Bruun, Mortensen and Harlou (Bruun et al., 2014), the building blocks of modular

Table 4
Definition of module components.

Group	Abbreviation	Components
A	EDC	Door control
B	DOD	Door frame
C	DDC	Emergency opening
D	EDG	Glass
E	IPL	Display panel
F	FST	Front structure
G	CST	Frame

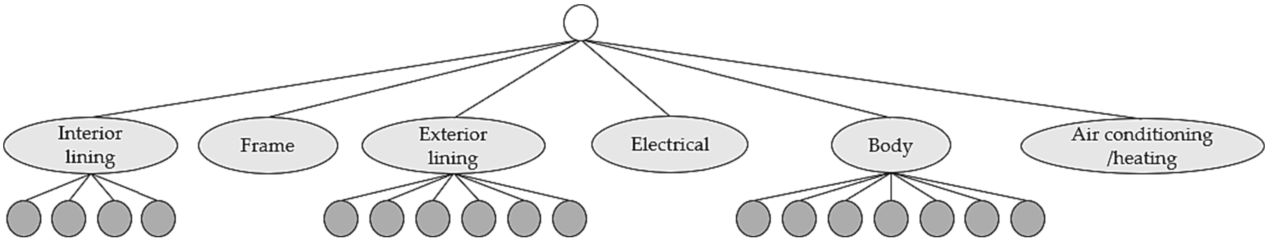


Fig. 21. Product hierarchical modular architecture.

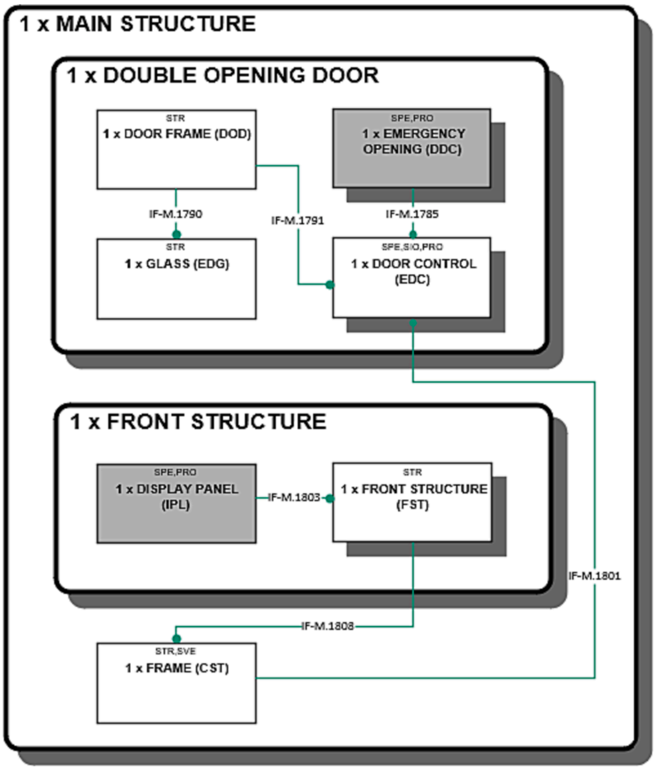


Fig. 22. Main structure interactions using the interface diagram.

product design can be established in the engineering and design teams of SMEs in the manufacturing sector.

After representing the interactions visually, it is important to suggest initiatives to standardize the interfaces between components in order to achieve interchangeability. However, standardizing the interfaces can result in changes in the components, and thus changes in the modular product design. Fig. 26 illustrates the feedback loop that can be established between the first and second step according to the modifications that can be generated by interface standardization.

Standardization workshops were therefore provided; first, for the two most complex modules, to reduce assembly variability, thereby ensuring standard interfaces, modules, and sub-modules. A multidisciplinary team was able to quantify the gains of standardization. Table 5 details the reduction achieved through standardization.

Standardization therefore reduced by 48.64 % the components related to the body and interior trim modules. Moreover, this work also reduced variability by increasing component interchangeability.

Finally, once the product structure has been clearly broken down into a modular architecture and once the interfaces and components have been standardized, the various configuration rules associated with the modules must be detailed. The configuration rules were defined, once again, by a multidisciplinary team, involving mainly members of the engineering and sales teams. To do this, the interface diagram offers the ability to import the product into an Excel configuration matrix, as shown in Fig. 17. The configuration rules per module according to the available templates are set up directly in Excel. Fig. 27 shows an

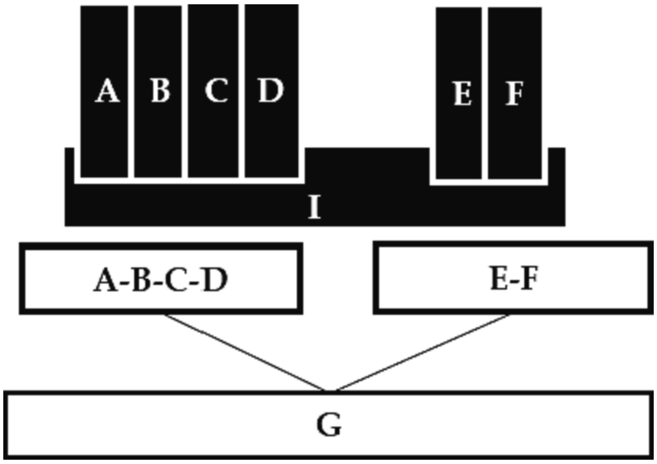


Fig. 24. Formation of the modules from the modular breakdown.

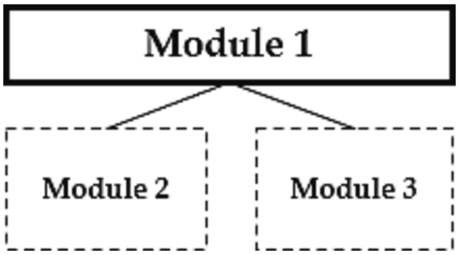
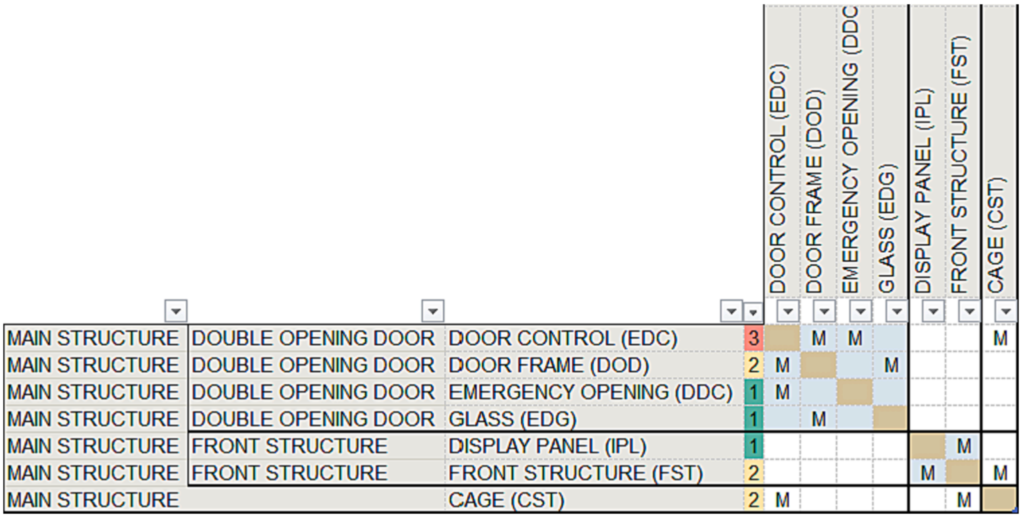


Fig. 25. Breakdown of three modules.



				DOOR CONTROL (EDC)	DOOR FRAME (DOD)	EMERGENCY OPENING (DDC	GLASS (EDG)	DISPLAY PANEL (IPL)	FRONT STRUCTURE (FST)	CAGE (CST)
MAIN STRUCTURE	DOUBLE OPENING DOOR	DOOR CONTROL (EDC)	3		M	M				M
MAIN STRUCTURE	DOUBLE OPENING DOOR	DOOR FRAME (DOD)	2	M			M			
MAIN STRUCTURE	DOUBLE OPENING DOOR	EMERGENCY OPENING (DDC)	1	M						
MAIN STRUCTURE	DOUBLE OPENING DOOR	GLASS (EDG)	1		M					
MAIN STRUCTURE	FRONT STRUCTURE	DISPLAY PANEL (IPL)	1						M	
MAIN STRUCTURE	FRONT STRUCTURE	FRONT STRUCTURE (FST)	2					M		M
MAIN STRUCTURE		CAGE (CST)	2	M					M	

Fig. 23. Module formation based on the modular breakdown.

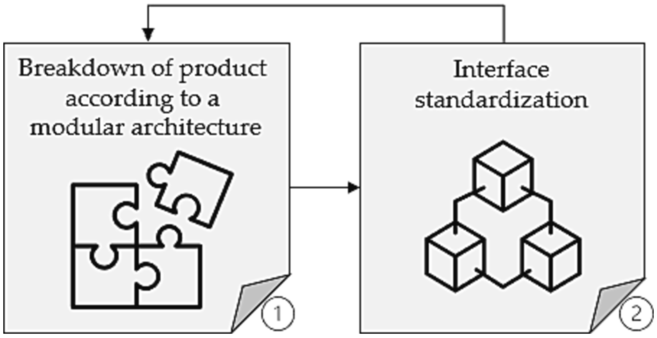


Fig. 26. Feedback loop between the first and second step.

Table 5
Component reduction by module.

Main module	Sub-module	Before standardization	After standardization
Body	Main structure	117	62
	Floor	115	39
	Rear structure	6	4
Interior lining	Front fibre	15	11
	Side skin	34	31
	Moreview	7	4
Total		294	151
Percentage of reduction		48.64 %	

example of the configuration rules that can be associated with a component of the door frame module.

This step can also be iterative. Indeed, several sessions were necessary to obtain a complete and viable result. Building this matrix containing the configuration rules is the last step in operationalizing the modular product design.

4.4. Validation

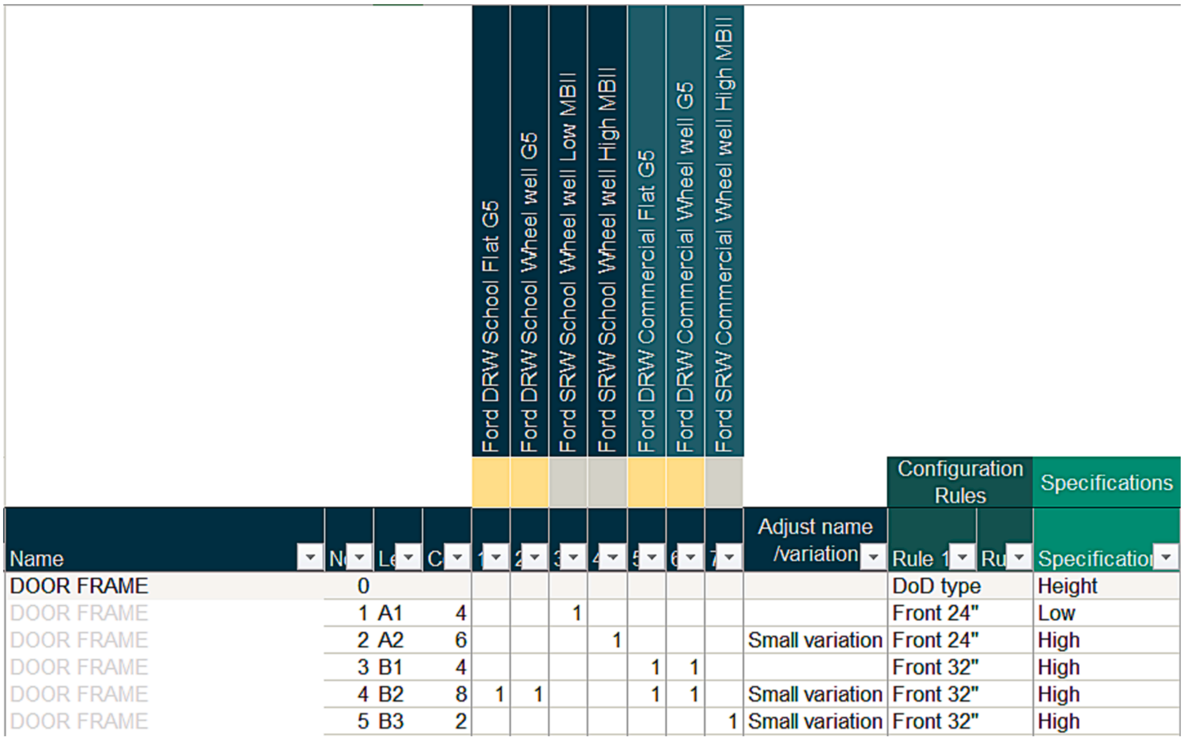
The stage-gate process includes a validation phase to ensure the strategy offered is valid. Once the matrices and tools have been used, it is important to verify the creation sequence, the connection between the tools and the product offered by the SME.

As a first step, the modular breakdown of the product was validated with the engineering team, before and after the matrix cutting tools were used. The result is in line with the current state of the product. In the second step, the interface diagram was created in accordance with the previously approved modular architecture. The interface diagram was then validated with the engineering team. Standardizing the interfaces required revising certain components and adjusting certain modules. Finally, the module configuration was validated theoretically with the help of the engineering and sales teams. By further exploring the link with the modular product design and the other transformation axes, the connection between the tools in place and those to be explored was also validated.

4.5. Implementation

The last step of the stage-gate process is the strategy implementation phase. After developing a strategy tested by a case study, the tools and results obtained during the stage-gate process were used to implement the strategy for operationalizing the modular product design within the SME. Fig. 28 adapts the strategy shown in Fig. 18 by specifying the possible progress of the steps and adding a feedback loop between step 1 and step 2.

After setting up the strategy for operationalizing modular product design, some suggestions were made. Indeed, an integration plan can be developed to facilitate the implementation of the developed tools. This plan can contain the new information processes that will be in effect and the methods for modifications and identify the key actors who can authorize changes in the product and its cutting. Implementing an integration plan can facilitate the modular changeover and better support the employees concerned in this change.



				Ford DRW School Flat G5	Ford DRW School Wheel well G5	Ford SRW School Wheel well Low MBII	Ford SRW School Wheel well High MBII	Ford DRW Commercial Flat G5	Ford DRW Commercial Wheel well G5	Ford SRW Commercial Wheel well High MBII		Configuration Rules		Specifications
Name	N	Le	C	1	2	3	4	5	6	7	Adjust name /variation	Rule 1	Ru	Specificatio
DOOR FRAME	0											DoD type		Height
DOOR FRAME	1	A1	4			1						Front 24"		Low
DOOR FRAME	2	A2	6				1				Small variation	Front 24"		High
DOOR FRAME	3	B1	4					1	1			Front 32"		High
DOOR FRAME	4	B2	8	1	1			1	1		Small variation	Front 32"		High
DOOR FRAME	5	B3	2							1	Small variation	Front 32"		High

Fig. 27. Door Frame Configuration Rule.

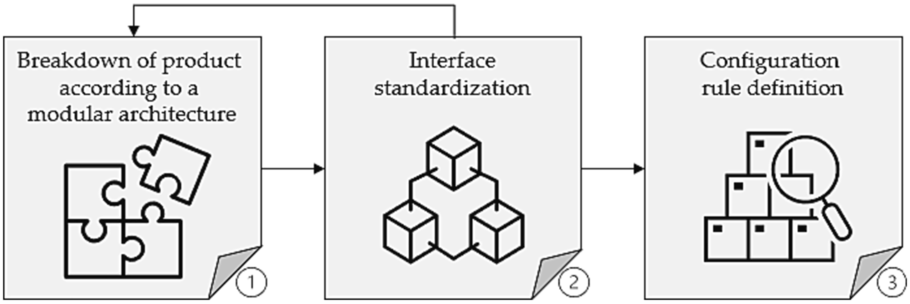


Fig. 28. Tested strategy for operationalizing modular product design.

5. Discussion

The literature suggests that mass customization helps companies to handle the context of personalized demand related to the increasingly high customer demand. It proposes certain factors that make it possible to implement mass customization in SMEs in the manufacturing sector to adapt to this new context. However, four factors stand out as being the transformation axes that make it possible to operationalize mass customization, but a sequenced and tested strategy is not offered.

The literature thus highlights the absence of a strategy for shifting to mass customization. However, modular product design emerges as an interesting starting point to begin this shift (Cohen and Pine Li, 2007; Aeknarajindawat and Chancharoen, 2019; Zhang et al., 2019; Shuyou et al., 2021). This study details a proposal including a three-step sequence, with the presence of a feedback loop between step 1 and step 2, using a stage-gate process to develop a three-step strategy: Product breakdown, Interface standardization, Configuration rules definition. Fig. 29 illustrates the framework of a strategy to enable SMEs in the manufacturing sector to move toward customized mass production.

Cutting the product according to a modular architecture made it possible to cut the product into six main modules. Furthermore, the standardization work made it possible to reduce by 48.64 % the components related to the main modules. Finally, defining the configuration rules made it possible to operationalize the modular design of the product by making it possible to implement the modules. The origin of the strategy striving for personalized mass production thus involves installing product modularity.

This overall strategy requires using various tools. Some of these tools already exist, while others need to be developed (Yu et al., 2007;

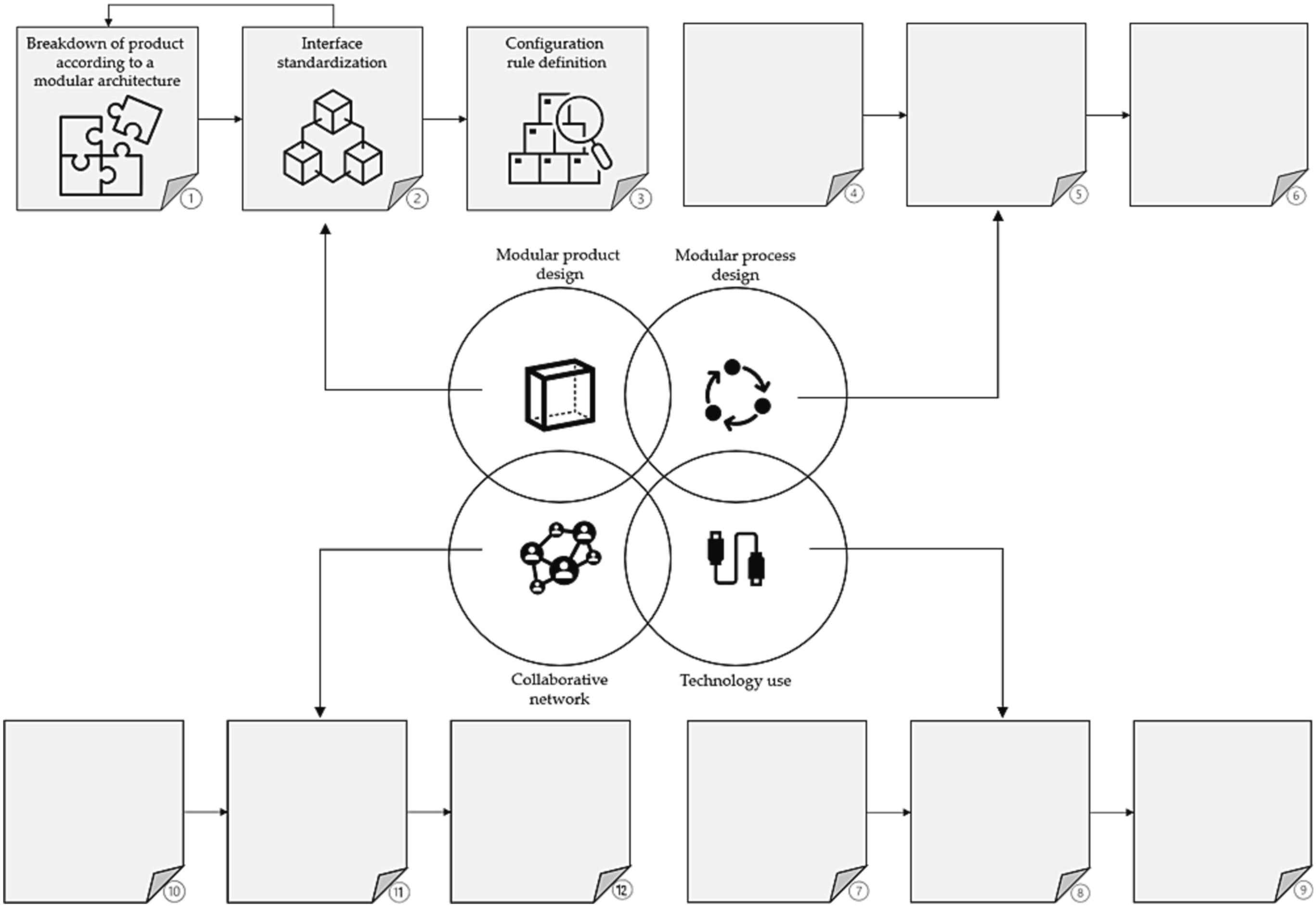


Fig. 29. Framework of a strategy for customized mass production.

Kulkarni et al., 2018, 2018; Sosa et al., 2007; Bruun et al., 2014). Indeed, using the DSM, the interface diagram and the configuration tools presented made it possible to start implementing this strategy. Tools were used in each step making it possible to implement modular product design. These tools were then used to configure and create the modules. Fig. 30 details the tools used, and the steps involved in creating the 3D CAD.

This strategy also requires making it possible to connect these tools and the IT systems already in place in the company, considering the human and temporal resources available within the SME. Although tools are proposed by Bruun, Mortensen and Harlou (Bruun et al., 2014), it must be possible to adapt the use of the tools to the needs of the SME. Indeed, each SME has its own very specific context with constraints specific to its reality. Within the framework of this study, it was important to take into consideration the legislative constraints and standards associated with the various geographical regions where the products are sold. Indeed, to consider the particularities of the different regions of the world, it was necessary to add configuration rules according to the countries, provinces, and states where the products are delivered and used. On the other hand, it was important to adapt to the company's strategic vision so that the implementation of this strategy would be in line with the projects already underway. In addition, the use of the interface diagram had to be adapted at the level of its modular cut to take into consideration the structure and the information flow of the existing product to ensure that it is viable with the processes in place at the engineering level.

However, using tools that facilitate the implementation of modular product design does not guarantee success. This research showed that it is also important to look at the information flow between tools and systems to ensure product modularity is viable and kept up to date.

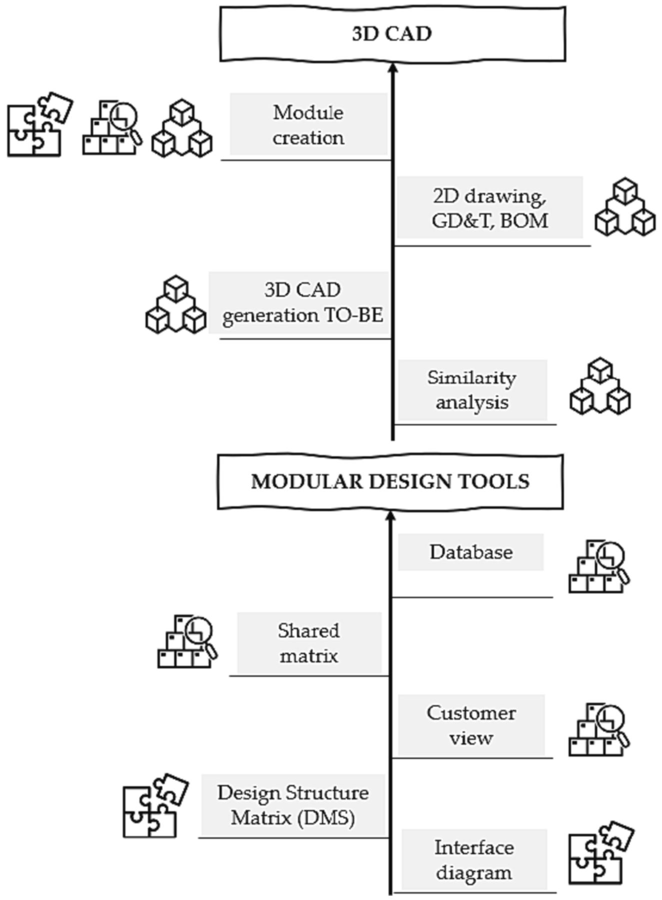


Fig. 30. Tools for implementing modular product design.

Fig. 31 details the information flow between the tools discussed in the article and the systems in place within the SME studied for this action research.

The tools used to implement a modular product design connect, via a database, to the systems already in place in the SME. This also provides a basis to begin implementing ERP software modules, such as the product configurator. This finding reveals the importance of implementing the other transformation axes, such as the use of technologies. Operationalizing modular product design requires the ability to connect and maintain the connection between the systems in place. In addition, to maintain the connection between systems, it is important to have clearly defined processes that are mastered by all actors: part creation process, part revision process, assembly creation process and assembly revision process. It can therefore be concluded that modular product design is a gateway to the other axes of transformation, i.e., modular process design, the use of technologies and the collaboration network.

In addition, as Early, Coletti and Juran (Early et al., 1999) propose that simultaneous engineering creates a close link between the market, the product design and the process, while including quality. Juran's trilogy puts forward planning, control and quality improvement (Early et al., 1999). Fig. 32 summarizes the planning steps for including the Juran trilogy principle in product development (Early et al., 1999).

Fig. 32 therefore illustrates the need to start with the modular product design, and then implement the other transformation axes. It is also important advance the principles of simultaneous engineering in the mass customization operationalization strategy. These principles systematically consider all the elements related to the product life cycle in the development of a product: design, manufacturing, supply, quality, etc. (Bullinger and Warschat, 2012). However, Fig. 29 demonstrates that the strategy is not complete and needs to be explored further. The other three transformation axes and their interconnections will need to be explored. Based on the principles of concurrent engineering and Juran's trilogy in product development, Table 6 details a future research agenda for understanding the next research directions and research opportunities to be advanced.

6. Conclusion

The objective of this study was to present the tools of an operational strategy using modular product design to make it possible for SMEs in the manufacturing sector to shift toward mass customization. This research achieved its objective by offering a strategy tested by a case study. The scientific contribution of this study proposes 4 axes of transformation to migrate towards mass customization: Modular product design, Modular process design, Use of technologies, Collaboration network. This article also highlights the need to tackle modular product design first, to migrate towards mass customization, by proposing a 3-stage strategy. Indeed, the relationship between modular product design and mass customization enables better integration of the other axes. The modular product design must then be transposed to production processes, while adapting existing technological systems and developing a distribution network adapted to modular design.

The strategy for operationalizing modular product design was developed based on the stage-gate process and the principles of concurrent engineering. This strategy goes through three steps and is supported using different tools: Product breakdown according to a modular architecture, Interface standardization, Configuration rules definition. The interface diagram, the DSM, the customer view, and the shared matrix are the tools used. A database was also created. A similarity analysis, CAD TO-BE generation, 2D drawing generation and module creation were also carried out.

This study has some limitations. The strategy and tools put forward address the first axis of transformation toward mass customization, without addressing the relationship with the other axes. Also, the strategy was implemented in two companies with different constraints: a product with standards and certifications to respect and a recreational

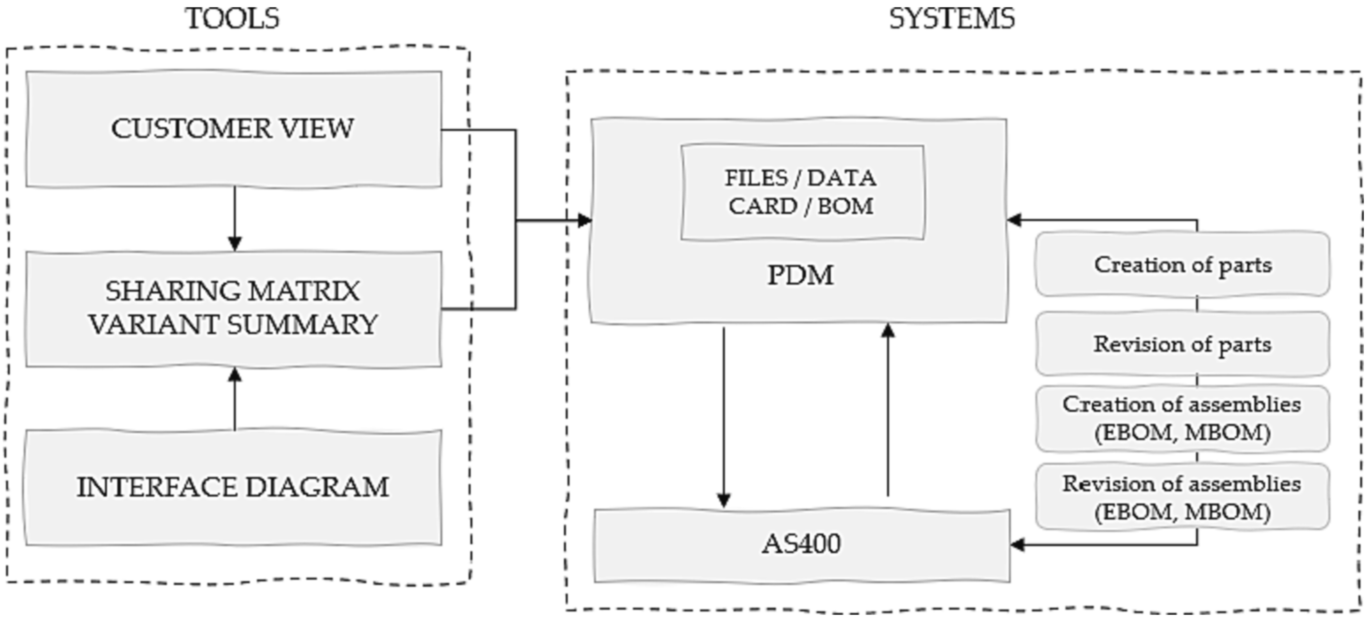


Fig. 31. Information flow between tools and systems.

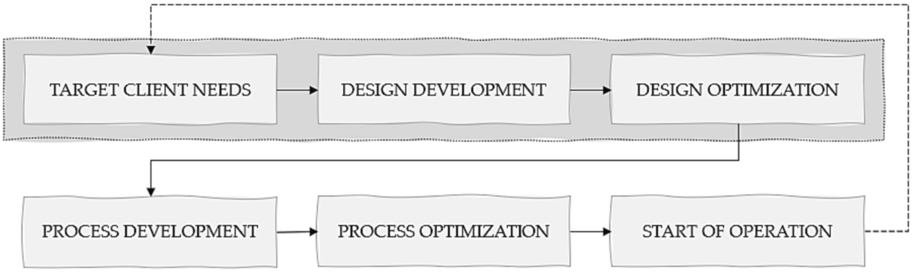


Fig. 32. Product development planning stages adapted from Early, Coletti and Juran (Early et al., 1999).

product. The strategy is generic to be adapted in an agile way to the different contexts of the companies but will have to be validated in different sectors. In addition, several challenges were encountered in relation to the company's context. Tool implementation schedules had to be revised several times to adapt to ongoing projects. A period of adaptation was also necessary to familiarize ourselves with the new tools in place.

This action-research enabled us to identify the success factors that favored the implementation of the tools in question. Indeed, management support throughout the project contributed to its success. Working with actors who believed in the success of the project facilitated creating and implementing this strategy. Also, resource availability and employee involvement contributed to the success of this research. These success factors enabled the strategy to be tested within the company despite the challenges encountered. Indeed, the involvement and support of the parties involved facilitated the implementation of this research, keeping the objective alive. However, the difficult procurement context forced a reprioritization of projects. This led to a slowdown in project execution. External constraints such as procurement delays, schedule revisions based on corporate priorities and the reorganization of strategic projects are all variables to be considered when implementing a strategy of this kind.

Future research should continue to develop the strategy for operationalizing mass customization by addressing the other three transformation axes and their interaction. In collaboration with a broader research program and several collaborators in the same research area, developing tools facilitating the implementation of mass customization in the SME manufacturing sector should be a focus of future research. Ultimately, future research could explore how a mass customization implementation strategy can build an agile network using distributed manufacturing and modular design tools. This future research could improve the strategy proposed in this study. Furthermore, by extending future research to the other transformation axes, it could be possible to offer a strategy that encompasses not only the product, but also processes, supply and technologies.

Author contributions

S.B.: Conceptualization, methodology, formal analysis, original draft preparation, visualization; S.G.: Conceptualization, methodology, validation, review and editing, supervision, project administration; G.A.: Conceptualization, methodology, validation, review and editing, supervision. All authors have read and agreed to the published version of the manuscript.

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9. Institutional review board statement

Not applicable.

Table 6
Future research program.

Research focus	Research opportunities	Potential research questions
Integrating modular product design with modular process design	Physical flow	• How can the gap between product and process be bridged? Will the product need to be revised based on the processes?
	Sustainability	• How can the link between the product and the process be maintained over time?
Operationalizing the modular process design	Process	• How should the process be adapted to the product? How are modular processes set up?
	Updates	• How will it be possible to force updates without burdening current operations?
IT tools interconnection	System architecture	• What system architecture will best fit the reality of a modular product? How can the architecture of existing systems be adapted?
	Informatics process	• What IT processes will need to be put in place to ensure the sustainability of the tools?
	Platform development	• What platform should be developed to support the existing IT tools? How will it be possible to maintain the connection between the different platforms/tools?
Implementing a collaborative network with a modular product	Collaboration	• How will it be possible to create a collaborative network using pro-product and modular processes? How will it be possible to make IT and employee tools communicate?
	Digitalization	• What role will digitalization play in this process?

10. Informed consent statement

Not applicable.

Data availability statement

Not applicable.

Conflicts of interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Stéphanie Bouchard: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Sébastien Gamache:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Project administration. **Georges Abdulnour:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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