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Integrating Modular Design Concepts for Enhanced Efficiency in Digital and Sustainable Manufacturing: A Literature Review

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Abstract: Small- and medium-sized manufacturing enterprises (SMMEs) face intense competitiveness, necessitating ever greater productivity. Enterprises struggle to meet the demand for customized products while maintaining their productivity. The transition from mass customization (MC) to mass personalization (MPe) leads to a further increase in product variety and, thus, complexity. Digital transformation alone is not sufficient to achieve MPe and traditional adoption of modularity no longer ensures enterprise competitiveness in this context of increased variety. The synergy between modularity concepts could enhance the efficiency of this design strategy. This study is part of a research plan to develop an effective modularity implementation strategy addressing MPe. The aim of this article is to identify the main concepts and tools to be considered in an implementation strategy. Concepts and tools are grouped into four combinations according to the level of product variety in different production strategies. This preliminary work serves as the foundational research for a larger research plan aimed at adapting and validating a modular product development strategy that incorporates these modularity concepts.

Keywords: modular design; mass personalization; mass customization; modularity; architecture; variety; complexity; manufacturing; Industry 4.0

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1. Introduction

SMMEs constitute an important part of the global economy, playing a crucial role in dynamism and innovation [1]. In a constantly evolving market environment, these companies seek to further customize their products to meet customer demand while maintaining their competitiveness [2,3]. Faced with product diversification, which generates additional complexity, many companies turn to an MC strategy aimed at configuring existing solutions [2].

MC is increasingly seen not as a sufficient competitive advantage to stand out from the competition but rather as an expected standard to remain competitive.

A transition from MC product offerings to MPe allows for differentiation through more personalized products. In MPe, the focus is on individual personalization to specifical address the client's needs. Compared to MC, MPe increases product offering variety, complexity, and is more focused on sustainable product development. MPe allows for greater competitiveness against other companies [4]. SMMEs present a variety of contexts, especially in terms of product variety, market, competition, and the flexibility of their production system. SMMEs orient themselves towards mass production (MP), MC, or MPe depending on their current situation.

At the heart of MC and MPe strategies lies the concept of modular design, which becomes a guiding principle to effectively manage this increase in product variety [5]. Modular design is a guiding principle of MPe, offering more personalized products than MC.

The literature presents several concepts of modularity, including product architecture, modular product breakdown, modular product platform, variety management, interface management, configuration, modular manufacturing, modularity metrics, and complexity management. Each concept features tools generally implemented individually and without an analysis of the synergies between them.

The partial implementation of modular design, in the form of an organic evolution of product families towards modular structures, is no longer sufficient to be competitive [6]. Alignment difficulties between enterprise departments regarding the objectives of product modular design lead to inefficiencies, resulting in only partial gains from its implementation [5].

What tools and methods for each modularity concept are best suited to the targeted production strategy (MC or MPe) to effectively address the increase in product variety while keeping complexity to a minimum? The hypothesis of this article is that groups of modularity concepts, when implemented together, can increase product variety while maintaining low complexity. These groups of tools with common objectives can help manage a large product offering at low costs, a considerable asset for the competitiveness of SMMEs.

This research is part of an extensive research plan enabling the development of an effective, successful, and sustainable MPe implementation strategy, including modular design in SMMEs. This article follows a previous partial modular strategy case study [7–9]. The goal of this literature review article is to identify the concepts, tools, methods, and approaches to be integrated into a modular design implementation strategy for SMMEs targeting MC or MPe. The tools are presented and categorized in a table according to the production strategy and the level of product variety. This preliminary work serves as the foundational research for a larger research plan aimed at adapting and validating a modular product development strategy that incorporates these modularity concepts. The article is divided as follows: Section 2—Research Context, Section 3—Discussion, Section 4—Conclusion, and Section 5—Future Directions.

2. Research Context

2.1. Research Context Methodology

The PRISMA method was used to select relevant articles for the literature review. For the identification stage, the Scopus database was employed with the keywords modular* AND manufacturing AND (custom* OR personali*), which returned 1546 results. During the screening stage, the inclusion of a word from each of the following two groups was required: (platform OR architecture OR design OR product) AND (variety OR variant OR interface); these were selected from the keywords of 11 relevant articles from the initial query. This refined search yielded 336 publications. In the inclusion stage, by reviewing abstracts, a final filter reduced the number of articles to be analyzed to 43 publications. This review also incorporates the snowballing method, taking into account the cited articles.

The research context outlines the objectives of different production strategies and explores the objectives of tools grouped under nine concepts. Figure 1 illustrates the introduction of the key concepts identified in the literature review on modular design, which are essential for developing a comprehensive modular design strategy for enterprises with limited resources targeting MC or MPe.

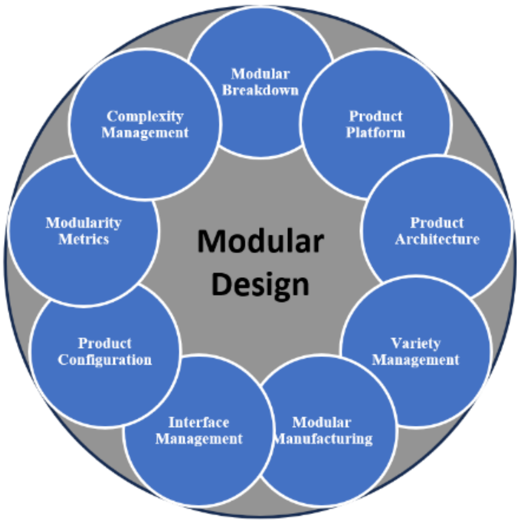

Figure 1. Key concepts to include in modular design strategy.

2.2. Production Strategy

The three production strategies, namely MP, MC, and MPe, each have specific objectives depending on the production volume and the variety of the product offering to be addressed. Identifying the objectives of these strategies will allow for the proper association of modularity tools with the appropriate production strategies.

2.2.1. Mass Production

MP aims to provide a product at low cost, with minimal customer involvement in product design since the products cater to multiple customers [10]. This strategy features a low variety of products and promotes design reuse, leading to limited variety in production, thus resulting in high efficiency and productivity [11,12]. Despite low production costs, products are designed and manufactured to exhibit high performance, where compromises are seldom allowed [13].

Thus, mass production has three main objectives: product performance, cost reduction, and low variety.

2.2.2. Mass Customization

MC features two main elements: a high level of product customization and pricing comparable to mass-produced items [3].

The high level of customization allows for meeting the individual needs of customers or closely matching those needs [3,14] since customers are limited to selecting a combination of options [4].

The second objective of MC is to produce this variety at mass production costs [3]. Good responsiveness, high production efficiency, and a flexible and stable production process [15] help to keep production costs at a low level [14]. Companies must, therefore, have volume efficiency and responsiveness to be able to quickly respond to this variety [16].

MC aims for two main objectives that can be divided into subcategories: increase the variety of the product offering via flexible design; maintain mass production costs via flexibility, agility, and economies of scale.

2.2.3. Mass Personalization

MPe is described as the subsequent step to MC. This higher level of personalization aims to satisfy the unique needs of customers, creating a “market of one” [10]. In MPe, the precise meeting of customer needs becomes more important than the price [17]. This production strategy emphasizes the active involvement of the customer [18]. The addition, removal, or modification of product features during its lifecycle provides an additional level of personalization throughout the product's useful life. Sustainability is pivotal in the MPe strategy, notably through product updates during its lifecycle [18]. MPe must maintain competitive pricing, delivery times, and quality [10].

The objectives of MPe include those of MC, like expanding the product range while keeping costs similar to mass production. Beyond MC's goals, MPe focuses on product individualization, strong customer involvement, updates throughout the product lifecycle, and the production of sustainable products.

2.2.4. Production Strategy Objectives

A recap of the objectives for each strategy is outlined in Table 1. The transition towards mass personalization (MPe) compels businesses to manage increased variety, thereby introducing rising complexity [5,19,20]. This shift necessitates greater flexibility and agility in design and production to accommodate product individualization. Besides addressing this variety at a low cost, moving to a MPe strategy must also cater to additional requirements such as customer involvement in their individualized product, product sustainability, and lifecycle updatability.

Table 1. Production strategies objectives.

Production Strategy Objectives	Mass Production	Mass Customization	Mass Personalization
Mass Production Cost	Present (Lowest)	Present (Lower than MPe but higher than MP)	Present (Low Compared to Custom Products but higher than MC)
Product Variety	Low Product Variety (Minimal to no choices)	Customed Products (Many configured choices)	Individualized Products (Unique product, market of one)
Product Performance	Present (No trade-off)	Absent (Some trade-off)	Absent (Some trade-off)
Design Flexibility and Agility	Absent	Present	Present
Design Updatability	Absent	Present	Present
Manufacturing Flexibility/Agility	Absent	Present	Present
Client Involvement	Absent	Present	Present
Lifecycle Updatability	Absent	Absent	Present
Sustainable Products Importance	Absent	Absent	Present

The selection of appropriate concepts and tools is crucial to meet the specific objectives of each strategy and to fully realize their potential. The adoption of modularity is a crucial concept for managing the variety and complexity of products inherent in MC and MPe strategies [5,14,21]. Several key concepts essential for developing a modular product design strategy will be elaborated upon in the following sections.

2.3. Product Architecture

Product architecture is defined as a grouping of functions and interfaces that connect functional, physical, and operational domains [22]. Product architecture identifies the link between a product's function and its physical components that fulfill this function [5]. The literature presents three types of product architectures: integral, modular, and open architecture.

2.3.1. Integral Architecture

Integral architecture is employed with the aim of maximizing a product's performance and minimizing production costs [5,13]. It is suited to a market that accepts few compromises in product performance. This architecture consists of clusters of dense or highly interconnected parts serving multiple functions and possessing interfaces that do not facilitate interchangeability [5].

The difficulty of interchangeability makes integral architecture more suited to MP or custom production that does not aim at reusing the design for creating a diverse range of products.

2.3.2. Modular Architecture

Modular architecture, on the other hand, consists of groups of parts called modules. These modules are common units across multiple products, catering to specific functionalities derived from market requirements [18].

Modular structures aim to increase external variety, that is, the range of products available to the customer [13,23,24]. To meet such a broad product offering, modular architecture establishes a usage plan, positioning rules and usage rules [25], as well as interfaces between these modules [26]. This structure enables increased design flexibility [5,27] and easier product changes [13], promotes module substitution and combinability, and enables the rapid incorporation of new technologies [27] and product improvement [5,20]. To be capable of producing such a broad range of products, modular architecture requires flexibility and agility at the production process level [18,28].

While offering a very broad range of products, modular architecture also aims to reduce the costs associated with this product variety. It achieves product segmentation that allows for the parallel design of modules [29], thereby reducing the time to market [25]. Some of these modules can be reused [22,29], thus reducing the time and design cost [14,22,25]. The reuse of modules and parts, thus, reduces internal variety [23,24], that is, the number of parts needed to meet the product offering. Reducing this variety of parts has the effect of keeping the company's internal complexity lower even when the product offering increases [2,26,30,31].

Modular architecture shares several objectives with MC. The structure of this product architecture enables short-term gains such as increasing the product offering and reducing the variety of parts. Longer-term gains are possible upon product improvement, redesign, or an increase in product offering.

2.3.3. Open Architecture

Similar to modular architecture, open architecture is based on the principles of modular design [18]. This type of architecture comprises standard and customizable modules, like modular architecture, in addition to personalized modules [4]. Open architecture targets a portion of the same objectives as modular architecture through the use of standard and customizable modules. These common objectives stem from the use of many of the same concepts, such as modular design.

Open architecture, however, goes beyond modular architecture. This architecture employs the concept of modules for manufacturing, as in modular architecture, but also in other product lifecycle stages. The use of modules throughout the product lifecycle emphasizes product modification and evolution during its useful life. Products can, thus, be repaired, upgraded with new functions, or recycled directly by the customer using the modular concept [18].

In addition to extending the product's lifecycle, the deployment of modules designed for disassembly [4] enables a focus on the end-of-life stage of products [18]. This approach is indicative of a shift towards a market that values sustainability, evident in the scalability of products and considerations for their dismantling.

Furthermore, the integration of personalized modules within open architecture fosters a degree of individualization for certain modules, achieved through a collaborative design process with the user. Product personalization is, thus, achieved through significant client involvement [4]. Such personalization can occur throughout the product's lifecycle, in line with the objective of employing modules throughout the product's lifespan.

Customer-driven personalization facilitated by open architecture aligns more closely with the context of MPe [4,18]. This approach not only increases product durability by enabling repairs but also aligns corporate strategies with sustainable development objectives. The practice of individualizing products during their lifecycle has the potential to foster and maintain enduring customer relationships throughout the duration of the product's life.

2.3.4. Product Architecture Selection

The objectives of each architectural type are aligned with a production strategy, respectively:

- MP and integral architecture;
- MC and modular architecture;
- MPe and open architecture.

The choice of architecture fundamentally guides the direction towards one of these production strategies. However, product architecture requires additional tools, which may vary depending on the context, to maintain its operationalization in daily business activities.

2.4. Modular Product Breakdown

The literature reveals a range of methods for dividing products into modules, each leading to distinct outcomes [29]. These methodologies have been classified into seven groups.

2.4.1. Functional Breakdown

Functional breakdowns entail a modular structure in which each module addresses a singular function of the product [20]. A variety of approaches can facilitate this functional modularization, including the behavioral-driven function–environment structure [29], the Functionnal Heuristic Method [29], Heuristics [23], Modular Function Deployment [23], and the Design Structure Matrix (DSM) [32]. These functional decomposition techniques confer multiple benefits, such as being conducive to new concept generation, enhancing the updatability of products [29], producing functionally decoupled design [20,30], reducing technical complexity [23], and promoting parallel design [29].

2.4.2. Physical Breakdown

DSM can also be utilized to categorize components within the matrix, thus generating a physical modular breakdown. DSM application significantly aids in designing complex systems, effectively streamlining both physical and functional decompositions. In physical decomposition approaches, it is imperative that the product's design is finalized before attempting modular decomposition, as understanding the interplay between components is crucial. Moreover, mapping out these interactions within matrices is a time-intensive process, necessitating considerable effort and analysis [29].

2.4.3. Combined Functional and Physical Breakdown

Axiomatic design introduces a hybrid strategy that encompasses both the functional and physical dimensions of product decomposition. This approach leverages the strengths of functional and physical breakdowns, especially the benefit of achieving functionally decoupled modules, thereby enhancing modular design's efficacy and flexibility [33].

2.4.4. Manufacturing Breakdown

Some researchers have introduced manufacturing decompositions that take into account production and assembly [34] or focus on reducing assembly time [20,33]. Such decompositions are advantageous as they allow for parallel pre-assembly processes, ensure that modules can be validated independently of the completed product [35], and aim to reduce the overall time required for assembly [20,33].

2.4.5. Client Requirement Breakdown

Quality Function Deployment focuses on translating customer requirements into design characteristics, effectively bridging customer needs with product functions [20] and enhancing customer satisfaction [36].

2.4.6. Modularity Type Breakdown

The decomposition approach bases its strategy on the specific modularity of each component to delineate modules [37], factoring in the cost and size of modules during the process [29]. This method proves beneficial even in scenarios marked by incomplete or missing data, especially during the design stages [29,37]. Additionally, it strives to segregate modules conducive to parallel development and to cluster components that exhibit significant interactions, optimizing the modular design process [37].

2.4.7. Lifecycle Breakdown

The last type of modular decomposition, lifecycle breakdown, can consider or integrate some modular decomposition methods from the other six groups, each serving a specific purpose or departmental needs. Lifecycle-based decompositions identify the rationale for each module's decomposition from a list of module drivers [23,35]. The constraints of various departments can be integrated into a modular decomposition method such as Module Process Chart [35] or Modular Function Deployment [23]. Modular decomposition methods based on the product lifecycle offer several benefits:

- Harmonized decomposition across all departments within the company [35];
- Considering various constraints such as product maintenance, service, sales, purchasing, and configuration [20,35];
- Including aspects like dismantling, recyclability, end-of-life considerations, and disposal, thereby promoting sustainable product lifecycle management [18];
- Facilitates decision-making amidst multiple simultaneous constraints and enhances modularity management [33];
- The ease of defining design variants [29];
- Facilitates make or buy decisions for modules [29];
- Reduces the total lifecycle cost of the product [29].

End-of-life considerations in lifecycle-based decomposition reveal a growing trend towards sustainability and environmental responsibility in the field of industrial design.

2.4.8. Product Breakdown Benefits

These methods enable the decomposition of the product into modules, facilitating efficiency in design. The literature showcases a wide array of modular decomposition methods, each with distinct objectives and advantages. Each method encompasses various considerations, benefits, and limitations.

Enterprises must be capable of selecting the most suitable approach for their specific objectives and needs. No single decomposition method appears to be universally superior, regardless of product variety or production strategies. The inclusion of configuration considerations or product variety as a split driver might be further adapted depending on the level of product variety, though this remains to be demonstrated. Only lifecycle-based decomposition appears to offer a solution more aligned with the current challenges in the literature, due to its interdepartmental alignment.

To select the appropriate method, Table 2 outlines the advantages and disadvantages of each group of modular decomposition methods, as discussed in the literature.

Table 2. Modular breakdown tools benefits.

Modular Breakdown Type	Functionally Decoupled	Generating New Concepts	Easy Design Updatability	Design Complex Systems	Enables Parallel Design	Time Consuming	Maximize Client Satisfaction	Identify Design Variants	Missing Information Context	Minimize Assembly Time	Separate Module Validation	Parallel Pre-Assembly	Make or Buy Decision	Total Lifecycle Cost	Department Harmonization	Product Sustainability	Lifecycle Consideration
Functional	[20,30]	[29]	[29]	[23,29]	[29]												
Physical				[29]		[29]											
Functional and Physical	[20,30,33]	[29]	[29]	[29]	[29]	[29]											
Manufacturing Process										[20,33]	[35]	[35]					
Client Requirements							[36]	[29]									
Modularity Type					[37]				[37]								
Lifecycle								[29]					[29]	[29]	[14,33,35]	[18,20]	[18,29]

2.5. Modular Product Platform

The literature delineates two predominant perspectives on defining the platform concept [27].

Definition #1 (set of stable modules) [38]: The first school of thought defines a platform as a set of stable parts, modules, or technologies common to a product family [13]. The platform concept aims to identify stable components for the entire product family and modules that offer variety to meet specific customer needs [27]. The reuse of this stable sub-assembly yields a competitive advantage by minimizing costs [5], due to economies of scale among the stable components [6]. The reduction in part variety or internal variety leads to decreased complexity. This same reuse of design results in enhanced design efficiency [25,27]. However, reusing a core of stable components to form a platform may result in reduced variety, reduced customization [39], and reduced speed of change [27].

Definition #2 (set of rules and interfaces) [40]: The second definition of a platform is characterized by its modular architecture, interfaces, and standard design rules [13]. Interfaces and rules enable flexibility in product design [25,41]. This flexibility leads to a greater variety of products without the need for design modifications [41] and improves time to market [25]. From this set of rules and interfaces, multiple products can be created by attaching new modules or technologies to the predefined interfaces without altering the platform [27]. The ease of integrating new modules and technologies enables this platform definition to accommodate a wide variety of products within the same platform [6].

Despite its increased flexibility, this platform concept facilitates the reuse of knowledge, interfaces, technologies, functionalities, and architectural rules, as well as the pooling of human skills and relationships. This common platform reduces the number of different elements [25] as well as complexity [31] and enables efficiency and effectiveness in design [13], as well as in many other tasks [25].

2.6. Variety Management

Product variety represents the complete range of products offered by companies to meet the diverse needs of different customers [25]. The size of the product range affects the company's competitiveness in the market. However, an increase in product variety incurs significant additional costs. Variety management seeks to optimize product diversification in order to reduce production costs while meeting market demand [32]. To distinguish between the variety to be maintained and the variety to be minimized, the literature identifies two groups of two types of varieties.

The literature defines internal variety as the diversity of parts, assemblies, and modules required for producing the product range [19,42]. External variety, on the other hand, relates to the size of the complete product offering as perceived by the customer [43]. The management of internal and external variety aims to reduce internal variety while maintaining or increasing external variety [23,32]. In other words, this is a balance between diversification and standardization [34]. Reducing internal variety leads to decreased complexity in both design and manufacturing [32].

Other strategies aim to reduce technical variety while maintaining or increasing functional variety [6,13]. This represents a balance between customer satisfaction and ease of manufacturability [42]. Functional variety is described in the literature as the components that provide differentiation in product functions, offering benefits to the customer. Technical variety encompasses the diversity in technologies, design methods, manufacturing processes, components, and assemblies required to achieve functional variety [11]. Technical variety is targeted for minimization through various variety-reduction programs [13]. Techniques for reducing technical variety aim to lower costs and enhance manufacturability [11].

Reducing internal variety requires examining the type of variety for each module, whether functional or technical. Functional and technical varieties apply at the module level, whereas internal and external varieties concern the entire product. Functional and technical varieties provide granularity that allows for a more nuanced management of variety.

2.7. Interface Management

In modular design, standard interfaces enable module interchangeability and independence, thereby limiting variety proliferation and promoting module reuse [25]. Reusing interfaces shortens the design time for new modules and updates [27]. Interface management enables companies to sustain their ability to offer a wide variety of products over time through the sharing and reusability of modules [18,27]. This variety is maintained or enhanced by the ability to adapt to changing customer demands and technological advancements [27]. A focus on the assembly and disassembly of modules through standard interfaces facilitates considerations at various product usage stages. These considerations lead to time savings in adding, upgrading, maintaining, or removing modules throughout the entire product lifecycle [18]. Such time savings facilitate lifecycle upgradability and product sustainability.

The literature also discusses the level of interface coupling. Coupled interfaces necessitate alterations to multiple components when a single component changes. Favoring decoupled interfaces, which reduce interdependence between modules, diminishes the redesign efforts required for changes. Prioritizing decoupled interfaces simplifies modifications, maintenance, and product upgradability without impacting overall system design [5].

Effective interface management is a crucial aspect of modular design, enhancing module reuse, enabling adaptation to market demands and technological changes, and directly impacting modular design efficiency. The choice between decoupled interfaces and standard interfaces depends on several considerations that are not clearly outlined in the literature. Decoupled interfaces appear to offer greater flexibility for product evolution and customization over time. On the other hand, standard interfaces seem to facilitate reuse and cost-effectiveness within the confines of the standard interface. An effective strategy could involve a combination of both approaches. This strategy would allow for the selection of the appropriate interface based on the level of innovation, required flexibility, and costs of each module within the product.

2.8. Modular Processes

Various concepts applied to production and supply chains enhance operational efficiency and flexibility to accommodate a wide range of products.

2.8.1. Production Cells

Production cells employ stable and flexible processes to manufacture a module and its associated variants. This production organization improves quality and delivery speed, especially in the context of modular products. The enhancement in delivery speed actually boosts the company's agility, thereby enabling the provision of a wide variety at low costs [3].

2.8.2. Mixed-Model Production

Mixed-model assembly lines and modular supply chains are employed as key facilitators to manage increased product variety. These two concepts reduce investment costs and enhance the ability to absorb demand fluctuations across various product variants [44].

2.8.3. Assemble to Order (ATO)

Modular design facilitates a shift towards an ATO production strategy, a growing trend in modular manufacturing [13]. Transitioning to an ATO production strategy allows for the postponement of final assembly operations. Postponing assembly leads to savings in inventory levels, stock safety, and reductions in delivery lead times [3].

2.8.4. Late Customization

Late customization involves postponing the assembly of customized or personalized modules. This concept aims to design and assemble the product such that customization is the final step, allowing for the storage and production of the initial product stages without knowledge of the specific order. Late customization contributes to savings in the costs of inventory for both finished products and work-in-progress products [13].

2.8.5. Outsourcing Design and Production—Distributed Network

The literature discusses the possibility of outsourcing production and design. In this scenario, the involvement of suppliers in product development impacts manufacturing processes and the configuration of the supply chain. Certain decision-making models in supply chain management benefit from the sharing of common components and modular structures [13]. Outsourced and decentralized module production reduces the complexity of the final assembly while transferring risk and responsibility to suppliers [44]. However, these practices can increase complexity due to the networks needed to accommodate customization and personalization [45].

2.8.6. Design for Manufacturing and Assembly (DFMA)

DFMA practices adhere to principles and guidelines that simplify the design of assembly and manufacturing. These practices necessitate collaboration between design teams and production teams. DFMA is important for reducing complexity in modular manufacturing [5].

2.8.7. Manufacturing Flexibility

The literature identifies three key components that enhance manufacturing flexibility: flexible resources, flexible equipment, and flexible automation.

Increased resource flexibility can be achieved through cross-training, the ability to switch tasks, and the capacity to learn new skills. Resource flexibility helps to prevent productivity losses due to high product variety. However, an excess of resource flexibility can lead to efficiency losses. Flexibility in equipment and automation allows for the production of a wide variety of parts without excessive setup times or performance variability [21]. These two concepts, thus, share the same objectives and benefits.

2.8.8. Flexible Manufacturing System (FMS)

An FMS is defined as a group workstations interconnected by a transport and storage system [46]. FMSs are flexible manufacturing systems [15] with reduced setup times, making them suitable for small-batch production [25]. FMSs are used to produce a large series of parts with low variation or customization [18].

2.8.9. Reconfigurable Assembly Line (RAL)

The RAL concept is similar to Mixed-Model Production. However, this model allows for the evaluation of module assembly selection based on demand, in addition to the capability to reconfigure the production system. It is no longer just about optimizing the production sequence of the current system. This type of system offers more advantages than Mixed-Model Production [47]. Its ability to reconfigure in response to increased demand for a particular module enables quicker adaptation to significant demand fluctuations between modules, especially in the case of a wide product variety.

2.8.10. Reconfigurable Manufacturing System (RMS)

RMSs feature a production system composed of multiple reconfigurable pieces of equipment. Various equipment configurations can produce the same part and a single configuration can produce multiple parts. The introduction of a new part into production may necessitate a revision of the production plans for several other parts [47]. RMSs enable cost-effective production in cases of high product variety [18] and increased efficiency [47]. RMSs are the best production system for unpredictable and changing markets. RMSs facilitate an open architecture [18].

Dynamic manufacturing systems facilitate simpler and scalable communication without increasing complexity with each additional technology or tool. These dynamic systems assess and, if necessary, perform a reconfiguration with every system change. These systems are more flexible and agile due to their decentralized architecture, which simplifies communications and facilitates scalability [48].

Reconfigurable automation applicable to these concepts requires rapid location changes to increase the agility and efficiency of the production system. Robots moving on automated guided vehicles could replace manual changes of automation equipment [48].

2.8.11. Modular Assembly

Modular assembly involves assembling several modules individually before integrating them on the main assembly line to create the final product [2,44,46]. Modular assembly facilitates the outsourcing of certain module productions while retaining only the main assembly line in-house [2]. In scenarios involving a wide range of products, modular assembly enables a reduction in complexity [44].

2.8.12. Strategic Modular Manufacturing Tool Selection

Certain tools and practices applied to the process stand out for their flexibility, agility, reduction of complexity, and efficiency in producing a wide variety of products. The adoption of these so-called modular production systems enables companies to offer a variety of products at a low cost as well as provide a swift response to the changing market demands. Certain process practices allow for greater or lesser flexibility, demonstrating the importance of selecting the right tools based on the level of product variety or module variety.

2.9. Configuration

Product configuration is based on a set of modules, rules, and constraints, thereby describing all the variants of products sellable to the customer [25]. Product configuration requires that each function of the product be addressed by a module in order to minimize interactions with other modules [32]. A product configurator retains configuration knowledge, thereby reducing errors at the technical specifications level [25]. These programs can be used by the seller or by the customer [47].

Other programs go beyond simple configuration. Specifically, the use of configuration–price–quotation (CPQ) software facilitates the product configuration process, the assignment of a price to the configured product, and the creation of a quote containing the information of the configured product [24].

Specialized sales tools, such as product configurators hosted on a website, allow customers to configure a product that meets their needs from the supplier's offerings [21]. Web-based product configurators support the ordering process, especially in an environment with a wide variety of products [13]. Web configurators enable customers to search for products by attributes, visualize the configured product, and receive real-time feedback on the manufacturer's ability to meet their individual needs, thereby increasing the volume of products sold [21]. Web configurators allow for the customization of products, thus better meeting the individual needs of customers [13].

Configuration in the context of modular products offers significant benefits, ranging from efficient customization to improved customer experience and commercial performance, when using appropriate tools and methods. The three solutions presented seem to vary mainly in their response to significant variety. The level of product personalization will lead a company to choose one or another of these solutions.

2.10. Modularity Metrics

The literature presents a considerable number of modular design measures. These measures have been categorized into eight groups. Each of these groups of modular design measures is divided into subgroups to clarify their composition.

Group 1 concerns measures aimed at determining a level of similarity or standardization at the level of parts, modules, or interfaces. Group 2 gathers measures that assess the level of interaction between components and the level of connectivity of interfaces by the number of interfaces between parts within modules, coupling between modules, or the level of exchange between modules. Group 3 focuses on measures that evaluate the degree of customization and variety of products. Group 4 assesses the size of modular systems and allows for the evaluation of the complexity of modular systems. Group 5 delves into evaluating the degree of modular design by the efficiency of modules or the functional independence between modules. Group 6 encompasses all measures of costs and the profitability of modularity. Group 7 includes all costs associated with the manufacturing department. Group 8 gathers measures that allow for comparisons between platforms. Table 3 presents the groupings of measures as well as the associated authors.

Table 3. Modular metric groups.

Group	Subgroup	Authors
Group 1: Commonality, Standardization, and Sharing	Similarity Indexes	[19]
	Components Commonality	[13,21,29]
	Commonality Index	[13]
	Optimal Commonality	[13]
	Component Sharing	[13]
	Commonality Cost Advantage	[13]
	Interface Commonality	[13]
Group 2: Connectivity and Interface	Component Connectivity	[5,13,29,49]
	Coupling Concept	[29,49]
	Flow Analysis	[36]
	Substitutability	[29]
Group 3: Personalization and Variety Level	Variety Index	[13]
	Degree of Customization	[3]
	Product Volume	[3]
	Customer Needs Rating	[13]
	Differentiation Level	[13]
	Variety and Differentiation Cost	[13]
	Product Variety Index	[13]
Group 4: Count and Size	DSM Size and Number of Modules	[5]
	Component Number	[13,27]
	Interface Number	[13]
	Minimal Description Length	[5]
Group 5: Modularity Level	Modular Grouping Index	[28]
	Functional Coupling	[13,29]
	Modularity Index	[5,13]
	Degree of Modularity (Integral vs. Modular)	[5]
	Function to Component Ratio	[13]
	Composition of Components	[13]
	Granularity Level	[13]
Group 6: Business Costs and Profitability	Discounted Cash Flow (DCF)	[13]
	Flexibility Value	[13]
	Profitability	[13]
	Product Cost	[27]
	Product Lifecycle Costs	[13]

Table 3. *Cont.*

Group	Subgroup	Authors
Group 7: Manufacturing Costs	Late Differentiation Costs	[13]
	Manufacturing Costs	[13]
Group 8: Multi-Platform Metrics	Similarity and Commonality	[12,13,30]

A thorough examination of modular design measures reveals their diversity. These groups of methods have different objectives. This diversity highlights the complexity of choosing tools and approaches without a clear guide.

2.11. Complexity Management

Increasing product variety incurs additional costs at several levels: extra time in design [45], a reduction in economies of scale, and the need for more service parts [35]. This product variety increase leads to a greater variety of parts in production, which increases uncertainties in the manufacturing process [5]. These uncertainties result in a loss of transparency in operations tracking, leading to difficult production control. This additional management, thus, incurs extra costs due to complexity management [35].

The literature primarily distinguishes between two types of complexity: static and dynamic. Static or structural complexity is defined by the number and variety of the products, components, or production system elements such as workstations and equipment. Dynamic complexity concerns the uncertainty and variation in company behavior, such as fluctuating product demand, production times, etc. [44,45].

Other more nuanced types of complexity are specific to manufacturing: choice complexity, transfer complexity, and feed complexity [44].

A complexity management approach aims to understand, control, and modify the design or planning in order to become more productive. To understand complexity, five groups of methods allow for its measurement and analysis: chaos and non-linear dynamic theory, information theory, hybrid, enumeration, and other methods [45]. In addition to modularity, other techniques can reduce complexity:

- Modifying the assembly sequence or the supply chain configuration [44].
- Using the Variant Mode and Effect Analysis (VMEA), a method for designing a modular product focused on market needs with a minimum number of variants [50].
- Reducing the number of platforms [34].
- Standardizing parts to reduce complexity, costs, and product development time [2,12].
- Grouping parts into sub-systems or a larger number of modules [2].

Understanding product complexity is essential for developing an effective modular strategy, as reducing complexity impacts the productivity of the manufacturing system [44]. Modular design is not the only way to manage and reduce complexity in a business [45].

2.12. Literature Review Summary Table

This literature review identifies the objectives of various production strategies, focusing on mass production, mass customization (MC), and mass personalization (MPe). It categorizes relevant tools, methods, and approaches under nine key modularity concepts and lists their objectives in relation to these production strategies. The results are summarized in a literature review table, providing an overview of the most suitable tools for each strategy based on product variety.

Table 4 details how the tools from each concept in synergy with modularity are aligned with the different production strategies. This table provides a detailed overview of the distinct objectives of each tool, thereby facilitating the selection of modularity tools according to the adopted production strategies.

Table 4. Literature review summary table.

Concept	Tool	MP			MPe											
					Common to MC and MPe								Specific to MPe			
					Increase Product Variety		MP Costs (Cost Reduction)						Increase Personalization			Sustainability
		Cost Reduction	Low Variety	Product Performance	Increase Product Offering	Design Flexibility Updatability Prod. Change	Economy of Scale by Internal Variety Reduction	Manufacturing Costs	Flexibility & Agility	Administration Efficiency	Design Efficiency	Complexity Reduction	Product Individualization	Involvement of Client	Lifecycle Updatability	Sustainable Products
Product Architecture	Integral	[13]		[5,13]												
	Modular				[13,23,24]	[5,13,27,29]	[23,24,26]		[18,28]		[22,25,29]	[26]				
	Open				[13,23,24]	[5,13,27,29]	[23,24,26]		[18,28]		[22,25,29]	[26]	[4,18]	[4,18]	[18]	[18]
Modular Product Breakdown	Functional					[29]					X					
	Physical										X					
	Functional and Physical					[29]					X					
	Client Requirements				[29]						X					
	Modularity type										X					
	Manufacturing							[20,33,35]			X					
	Lifecycle				[29]			[35]		[35]	X				[18,29]	[18,20]
Modular Product Platform	Def.1: Commons Parts	[5,27]			[5,27]		[5,6,27,34]			[25]	[25,27]	[27,34]				
	Def.2: Rules and Interfaces				[6,13,31]	[25,27,41]	[13,27]			[25]	[13,25]	[25,31]				
Variety Management	Internal /External				[19,32]		[19,32]					[32]				
	Functional /Technical				[6,11]		[6,13]	[6,11]								
Interface Management	Interface Standardization					[27]	[18,25]				[27]				[18]	[18]
	Interface Decoupling					[5]					[5]				[5]	

Table 4. *Cont.*

Concept	Tool	MP			MPe											
					Common to MC and MPe							Specific to MPe				
					Increase Product Variety		MP Costs (Cost Reduction)					Increase Personalization			Sustainability
		Cost Reduction	Low Variety	Product Performance	Increase Product Offering	Design Flexibility Updatability Prod. Change	Economy of Scale by Internal Variety Reduction	Manufacturing Costs	Flexibility & Agility	Administration Efficiency	Design Efficiency	Complexity Reduction	Product Individualization	Involvement of Client	Lifecycle Updatability	Sustainable Products
Modular Manufacturing	Mixed-Model Production							[44]	[44]							
	Cellular Manufacturing							[3]	[3]							
	RAL								[47]				[47]			
	Manuf. Flexibility							[21]	[21]							
	FMS							[18]	[10,15,25]							
	RMS							[47]	[47]				[18,47]			
	ATO							[3]	[3]							
	Late Customization							[13]								
	Distributed Network/ Outsourcing								[13]			[44]				
	Modular Assembly											[44]				
	DFMA											[5]				
Configuration	Product Configurator									[25]				[47]		
	CPQ									[25]						
	Web-Based Configurator									[25]			[13]	[21]		

Table 4. *Cont.*

Concept	Tool	MP			MPe											
					Common to MC and MPe								Specific to MPe			
					Increase Product Variety		MP Costs (Cost Reduction)						Increase Personalization			Sustainability
		Cost Reduction	Low Variety	Product Performance	Increase Product Offering	Design Flexibility Updatability Prod. Change	Economy of Scale by Internal Variety Reduction	Manufacturing Costs	Flexibility & Agility	Administration Efficiency	Design Efficiency	Complexity Reduction	Product Individualization	Involvement of Client	Lifecycle Updatability	Sustainable Products
Modularity Metrics	Commonality and Std.						X				X	X				
	Connectivity and Interface					X					X				X	
	Personalization and Variety				X								X			
	Count and Size											X				
	Level of Modularity					X										
	Business Costs/Profitability															
	Manufacturing Costs							X								
	Multi-Platform Metrics						X				X	X				
Complexity Management	Static/Dynamic Complexity							[44]				[44]				
	Manufacturing Complexity Types							[44]				[44]				
	Assembly Sequence/ Supply chain Configuration											[44]				
	VMEA				[50]		[50]					[50]				
	Reduce Platform Quantity											[34]				
	Part Standardization	[2,12]	[12]					[2,12]			[2,12]	[2,12]				
	Sub-Systems /More Modules											[2]				

The "X" marks presence in the matrix without specific references; it is included to indicate the synthesis of information from various other sources cited in the literature review. These marks indicate the presence of a relationship or relevance of certain tools and concepts to particular production strategies, even if a direct reference is not provided for each specific instance. This approach ensures that the matrix comprehensively represents the connections identified through the overall analysis of the reviewed literature.

3. Discussion

Based on the summary presented in Table 4, the discussion proposes four groups of concepts to adopt in a strategy for implementing MC or MPe. Table 5 identifies these groups of concepts based on the product variety level. Grouping concepts by product variety level helps tailor the modularity strategy to the specific needs and complexities of different production environments. Higher product variety necessitates greater flexibility in both design and production, requiring different tools and more focused needs. The operationalization of these key concepts by group can be established in subsequent research.

Table 5. Modular design concept synergy analysis.

Concept	Tool Selection Method in Table 4	Product Variety Level			
		Low	Medium	High	Very High
		Mass Production	Mass Customization		Mass Personalization
Product Architecture	Select appropriate based on variety	⬤	⬤	⬤	⬤
Product Breakdown	Select 1 from list considering Tables 2 and 6		⬤	⬤	⬤
Modular Platform	Select 1 or combine both	⬤	⬤	⬤	⬤
Variety Management	Select 1 or combine both		●	⬤	⬤
Interface Management	Select 1 or combine both		•	⬤	⬤
Modular Manufacturing	Select appropriate considering business context		•	●	⬤
Configuration	Select appropriate based on variety		●	●	⬤
Modularity Metrics	Select based on concept implementation and variety		•	●	⬤
Complexity Management	Select based on business complexity and modularity metrics			•	●

Legend: ⬤—Essential concept to include in modular strategy. ●—One Concept to seriously consider including in modular strategy. •—Concept should be considered in modular strategy.

Table 6. Modular design tools synergy analysis.

Concept	Tool	Product Variety Level			
		Low	Medium	High	Very High
		MP	MC		MPe
Product Architecture	Integral	☑			
	Modular		☑	☑	
	Open				☑

Table 6. *Cont.*

Concept	Tool	Product Variety Level			
		Low	Medium	High	Very High
		MP	MC		MPe
Modular Product Breakdown	Functional		☑	☑	
	Physical		☑		
	Functional and Physical		☑	☑	
	Manufacturing Process		☑		
	Client Requirements		☑	☑	
	Modularity Type		☑	☑	
	Lifecycle		☑	☑	☑
Modular Platform	Def.1: Commons parts	☑	☑	✓	✓
	Def.2: Rules and interfaces		☑	☑	☑
Variety Management	Internal/External		✓	✓	✓
	Functional/Technical		✓	☑	☑
Interface Management	Interface Standardization		☑	☑	☑
	Interface Decoupling		☑	☑	☑
Modular Manufacturing	Mixed-Model Production		☑	✓	✓
	Cellular Manufacturing		☑	☑	✓
	RAL				☑
	Manufacturing Flexibility		(✓)	✓	☑
	FMS		☑	☑	(✓)
	RMS				☑
	ATO		✓	☑	☑
	Late Customization		✓	☑	☑
	Distributed Network/Outsourcing		✓	☑	☑
	Modular Assembly		✓	☑	☑
	DFMA		(✓)	✓	☑
Configuration	Product Configurator		☑	☑	
	CPQ		(✓)	✓	☑
	Web-Based Configurator			☑	☑
Modularity Metrics	Commonality and Standardization	☑	☑	✓	(✓)
	Connectivity and Interface		(✓)	☑	☑
	Personalization and Variety		(✓)	✓	☑
	Count and Size		☑	✓	(✓)
	Level of Modularity		(✓)	✓	✓
	Business Costs/Profitability		(✓)	(✓)	(✓)
	Manufacturing Costs		(✓)	(✓)	(✓)
	Multi-Platform Metrics		(✓) *	✓ *	☑ *
Complexity Management	Static/Dynamic Complexity		(✓)	✓	☑
	Manufacturing Complexity Types			(✓)	(✓)
	Assembly Sequence/ Supply Chain Configuration			(✓)	✓
	VMEA		(✓)	(✓)	✓
	Reduce Platform Quantity			(✓) *	✓ *
	Part Standardization		✓	✓	✓
	Sub-Systems/More Modules		(✓)	(✓)	✓

Legend: ☑—One of the essential options to be implemented, ✓—Option should be seriously considered, (✓)—Option should be considered, * Tools for Businesses Operating Across Multiple Product Platforms

Table 5 highlights an important point: the higher the product variety level, the more relevant the adoption of structured tools and the focus on flexibility and agility become in design and manufacturing. The analysis also indicates that modularity measures and complexity management gain importance with a higher product variety level, i.e., increased complexity.

The analysis also points out the presence of three fundamental concepts for both MC and MPe, namely product architecture, product decomposition, and modular platform. These three elements, thus, form the base upon which other modularity concepts rely.

Table 5 clearly illustrates that it may be relevant but not necessary to implement additional concepts in contexts of medium variety. Structured tools are, thus, less essential in the case of a low or medium product variety level.

To guide the selection of appropriate tools for each concept, Table 6 was created based on the literature review and Table 4. This table illustrates the relationship between the levels of product variety and the recommended modularity tools.

In addition to guiding the choice of tools for creating a modularity implementation strategy, analysis of the table has identified nine findings, one finding per concept, as well as three general findings.

3.1. Findings for Each of the Nine Concepts

Each product architecture choice targets a single production strategy: integral for MP, modular for MC, and open for MPe. The presence of product architecture across all strategies might indicate that it is a prerequisite to other concept choices.

Each type of modular breakdown can be selected based on its specific advantages. The choice of modular breakdown does not appear to be determined by product variety. The choice of breakdown type might be influenced by the advantages of certain methods, notably product and systems complexity, the type of product architecture, and assembly complexity.

Product platform definitions are adapted to different levels of variety. However, a set of standard modules can coexist with a set of rules, interfaces, and positions. The two definitions of platforms could complement each other and result in benefits from reduced production costs and product flexibility. The idea of having a product platform, defined as a set of stable modules could penalize cases of high variety by limiting product flexibility.

Variety management, always aims at balancing customer satisfaction and reducing complexity. Variety management tools precisely target the objectives of MC and MPe, highlighting their importance from the presence of variety. The technical/functional variety seems to be more concrete and applicable due to its more precise level of abstraction.

Interface management becomes more important with a significant change in product variety. Interchangeability becomes a priority when product complexity becomes unmanageable. To achieve effective interchangeability between modules, the modular strategy requires a more structured application and tighter management of interface control.

Modular manufacturing tools primarily aim for mass production at low costs. To achieve this, the majority of these tools aim to increase production flexibility and agility to accommodate a wider variety while keeping costs low. These practices have little or no impact on product variety.

Configuration is a concept whose tools allow for more efficient management of the sale of all this product variety. These tools are essential for collecting personalized needs and involving the customer in the design of individualized products.

Certain modularity measurement groups appear to be more suited depending on the product variety level. However, most measurement groups seem to measure one of the first seven concepts presented. The associations of measurement groups with the following concepts could be studied more in depth:

- Commonality and standardization with the product platform concept;
- Connectivity and interface with the interface management concept;
- Manufacturing costs with the modular manufacturing concept;
- Personalization and variety with the variety management concept.

Complexity measures and complexity reduction methods become more relevant with the increase in product variety or in the presence of complexity. Static complexity is much more relevant in the context of modularity since design has a direct impact on internal variety and is closely linked to static complexity. These tools complement the preceding concepts.

3.2. General Findings

Tools for sustainable modular products focus on open architecture, modular segmentation based on the lifecycle, and interface management for easy disassembly at end-of-life. The literature seems to present few tools adapted to the development of sustainable modular products. Specifically, measures on product sustainability or considerations for each of the concepts at the level of product sustainability could be developed. These additional tools would be necessary for the development of a sustainable modular implementation strategy for MPe.

The analyses conducted present groups of tools aligned with a production strategy of MC or MPe and the same objectives. The creation of synergies between these groups of tools for each context would allow for better integration. From this better integration between concepts, a reduction in the time and resources required to design and manage modularity in companies could result. The reduction of resources required to implement an effective and successful modular strategy could make these strategies more accessible to SMME. Adapting concepts and tools to SMME requires them to be simple and accessible.

The analysis of the tables in this article does not clearly allow for the selection of all tools for developing a modularity implementation strategy. To better select tools for designing a strategy adapted to the context of each company, identifying additional selection parameters and the level of variety would be necessary.

3.3. Synergies and Adaptation to Enterprises with Limited Resources

To validate the presence of synergies between concepts, the integration among concepts could be tested for each of the proposed trajectories in a business environment. This approach would allow for defining how different modularity concepts can integrate coherently.

For enterprises with limited resources, adopting these strategies requires a gradual approach due to limited resources. Developing an implementation sequence is crucial to address this context. In cases of high product variety, it becomes essential to determine which solutions to prioritize, given the multitude of tools that can be implemented. Prioritization through an analysis of expected benefits could guide enterprises with limited resources in developing a strategy adapted to their contexts and constraints.

The question of adaptability feasibility in enterprises with limited resources remains unanswered in the literature.

3.4. Literature Review Limitations

This literature review primarily focused on modularity in the contexts of MC and MPe, omitting a detailed exploration of path implementation for customized products and excluding tools specific to mass production. It is limited to nine specific modularity concepts without considering the human aspect, organizational challenges, or the resource constraints.

4. Conclusions

This literature review presents nine key concepts essential for developing a comprehensive modular design strategy. These concepts, along with their relevant tools and methods, must be integrated into current product development strategies. Four groups have been created based on production strategies that will allow the selection of appropriate tools according to the level of product variety. This preliminary work is part of a larger research plan aimed at adapting and validating a modular product development strategy that incorporates these modularity concepts. Hence, this article serves as foundational research.

5. Future Directions

Future research could focus on several key areas. One key area is mapping out the specific stages at which each modularity concept and corresponding tools should be applied within the product development process.

Another area is developing guidelines for integrating specific tools at each stage to enhance modularity.

Additionally, creating adaptable frameworks that allow for the adaptation of modular strategies is important.

Integrating Industry 4.0 technologies into a modular design strategy can lead to more flexible, responsive, and sustainable manufacturing systems that can handle the complexities of mass customization and personalized production.

When dealing with product variety and a modular strategy, all nine concepts should be utilized, with variations occurring only in the selection of tools based on the unique needs and limitations.

Future research should also focus on the limitations of this study, including the human aspect, organizational challenges, leadership, modular training, and project planning. Including all these aspects would address actual problems highlighted in the literature and increase the chances of successful implementation.

Combining all these key areas could lead to the development of an adaptive strategy for modular product design that leverages the benefits of Industry 4.0.

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