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PRODUCT AND PROCESS MODULAR DESIGN: A REVIEW

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Abstract: *Enterprises struggle to survive in today's socio-economic environment characterized by globalization, shorter product lifecycle, demand for increased product variety and customized products, exponential technological development, and high uncertainty. Flexible, agile and reconfigurable manufacturing systems based on a modular product and process allow enterprises to survive in this environment. Modular design permits providing high product variety and flexibility with reduced costs. Product modular design is an old concept, but modular process is relatively new. There exist many research works on both methods, yet seldom are those considering integrated product/process modular design. This paper presents a review on both product and process modular design and highlights limits in an integrated approach.*

Keywords: Modular product design; Modular process design; Modularity; Reconfigurable manufacturing systems, Mass customization.

1. INTRODUCTION

Nowadays, enterprises have been facing a highly competitive market. In addition, the technology development for the manufacturing systems allows new production strategies previously impossible. The shorter product life cycles, the uncertainty of demands and the higher client's exigence for quality and variety in production are also remarkable. Consequently, companies have been adopting mass customization (MC) as a competitive strategy for surviving in this context. MC is defined as "the ability to provide customized products or services through flexible processes in high volumes at relatively low costs" [1].

Figure 1 represents some enablers for MC implementation. They can be organized in three main fields: process at the first column, management at the second and product at the third one. One main foundation of MC is modularity (or modular design) [2].

According to Hoek and Weken [3] and Tu et al. [4], modularity promotes the product variety in a high volume, by interchanging a limited number of standard sub-assemblies (modules) in order to produce many different finished products. Further, modularity is the key to enhance the cost-variety trade-off in the development of product family, by enabling specific changes to be made in the last stage of the production process [5]. It allows postponement and, consequently, the product customization, since the customers are able to change some parts of the product, without changing the whole one [6] [7].

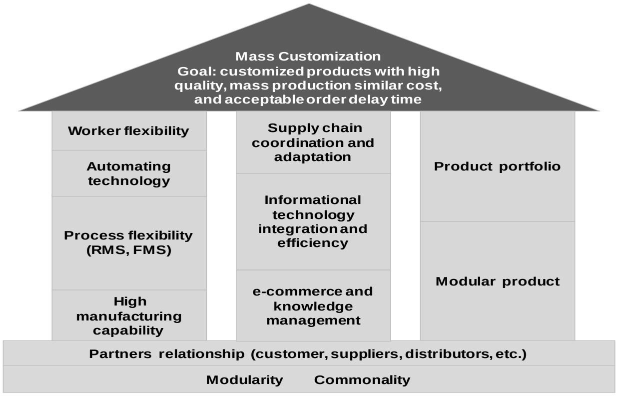

Fig. 1. *The house of Mass Customization (MC).*

This research is intended to better understand how the Modular Product Design (MPD) and Reconfigurable Manufacturing System (RMS) have been treated in literature, in order to apply these concepts for MC in a future work. This paper is organized as follows: section 2 describes the methodology, section 3 presents the literature review, section 4 a critical analysis of the literature review concerning product and process modularity in the last years. Finally, a conclusion and some suggestions for future researches are presented in section 5.

2. METHODOLOGY

There are several areas addressing modularity such as engineering, computer science, biology, architecture and arts [8], however this paper only took into account researches published in the mechanical and industrial engineering fields (product and manufacturing design and management issues). The general aspects about how modularity has been addressed in product and process design in scientific literature is presented.

The search for related papers was conducted in three databases: Google Scholar, Science Direct and Taylor and Francis, considering the last 20 years, it means between 1997 and 09/2017. At first, general keywords were used: "Product and system modular design", "Modularity", "Reconfigurable manufacturing system", "Product modular design", "Process modular design".

Secondly, more specific concepts were searched such as “Modules selection”, “Modules development”, “Product-platform design”, “Modules identification”, “Process reconfiguration”, “modular cellular manufacturing”. The keywords used were “Product and system modular design”, “Modularity”, “Reconfigurable manufacturing system”. Papers were selected A filter was used to select only papers from conferences and journals that accomplished engineering and management areas dated within the above mentioned period, which resulted on the selection of 192 papers.

Then, after further reading and analysis of the 192 papers, only 100 of them were kept. It is important to highlight that only articles focusing on modular design issues were considered, which helps to explain the expressive reduction on the number of research works.

The articles were divided into four classes: assembly system design, integrated design, reconfigurable manufacturing system design and modular product design. Integrated design aims at simultaneously studying product and process (manufacturing or assembly) modular design issues. After further reading and analysis of the selected papers, only 100 papers were kept. The graph presented in Figure 2 shows the papers classification in each area.

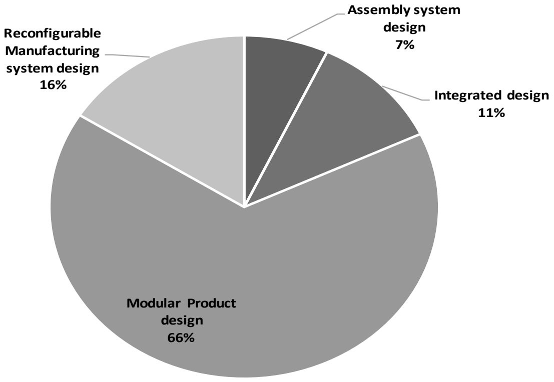

Fig. 2. *Number of publications by subject.*

After selecting and classifying the databases by the above-mentioned criteria, other analysis was achieved. The purpose was to investigate among the different classes of articles how the authors have addressed modular design by answering the following questions:

1. How modular design was addressed over the years?
2. Which journals/conferences have a higher number of publications?
3. Which were the most current used methods or approaches in modular design?
4. Which were the limitations of the identified research works?
5. Do they address mass customization issues?

All those answers will be presented in the Results and analysis section.

3. LITERATURE REVIEW

Modular Product Design provides high variety and flexibility with reduced cost [9]. A modular product is composed by several independent sub-assemblies, known as modules, that can be treated as logical unities yet perform as a whole [10] [11] [12]. Further, Allen and Carlson-Skalak [13] state that a module is a group of components, which can be separated from the product as a unit without destroying the whole product.

Lai and Gershenson [14] in turn, state that each module holds many components, which have a high level of dependency between them, whilst containing minimized dependencies and similarities among other components outside the module. It means that the components re-design in a module will not impact components from another module, confirming the statement of Baldwin and Clark [11].

Regarding the purpose of MPD, one can say that modular product is a function-oriented design, in which each module is responsible for executing one or more functions, that can be integrated into distinct systems with small changes [15] [16].

According to Ulrich [17], MPD is based on two main concepts: (1) similarity among physical and functional architecture, being described by an assortment of functional components linked with each other by exchanging signals, material and power; and (2) minimization of incidental interactions between physical components.

Regarding MC, modular product design can be organized in two main stages, as follow [18]:

1. *General product design:* is related to module definition, modules interfaces development and product platform design, which correspond to the steps 1, 2 and 3 presented in Table 1. These steps are responsible for designing the product family, which is a cluster of products that will share the same product platform and the manufacturing cells (modules).
2. *Specific product design:* is related to the selection of modules that will build together the final product, based on satisfying specific customer’s requirements and product variations among a product family. Among the product platform, modules can be added, removed or even changed in order to better satisfy customers exigence [19]. This stage is represented by the 4^{th} step from Table 1.

Table 1. Steps of *modular product design.*

#	Definition	Description
1	Modules Definition	Establishing the cluster of components that forms a module.
2	Modules interface development	Determining how the components will be arranged between/within modules.
3	Product platform design	Clustering the modules that will compose a common base were the differentiation will take place.
4	Modules identification	Selecting modules that will be assembled together.

Modular products are really present in people daily lives, varying from desktop personal computers, power tools, consumer electronics to automobiles and aircrafts [20][21]. Although the most common examples of modular products arise from the high technological and electronic products, a very simple and didactic example can be found in the food sector, more specifically in Subway®, a multinational fast food company of sandwiches. According to their own needs, each client can customize their final product, sandwich in this case, which is composed of five main modules: bread, cheese, meat, sauce and salad. For each module, it is possible to choose different flavors or types, that represent its instantiations.

Although the concept of modular product design has already been highly explored in literature, the process modular design is relatively a new one [4] [21] [22]. Regarding the modularity from a process perspective, one might say that it incorporates the idea of a dynamic network, in which each production module is relatively autonomous from the other, and can be quickly reconfigured to hasten new product launches [23].

According to Zhou and Shahrukh [24] each module can be called as “layout module” (or manufacturing cells), which are responsible to produce family parts. Indeed, machines will be clustered according to the processes operations required for each good, characterizing the Cellular Manufacturing, which is known as an approach to improve flexibility and efficiency compared to just in time and flexible manufacturing systems [25].

In this sense, arises the concept of reconfigurable manufacturing systems (RMS), which is designed with the purpose of changing faster process architecture structures, as well as their components, in order to make rapid adjustments in production capacity and functionality to respond to abrupt variations in market demands or in controlling requirements [26]. RMS is considered a complex system, that can be designed by using different strategies, such as modular design [27]. Actually, process modules are the unities that will be assembled (changed, added or removed) to (re)configure the manufacturing system [28] [29].

Thus reconfigurable manufacturing and cellular manufacturing shared the principle of modularity in their design. Moreover, RMS can be constructed from cells as presented by Koren et al [30].

The design of reconfigurable cellular manufacturing is similar to product design, but instead of product modules, process cells, e.g process modules, are addressed [22] [31]. The main difference between product and process design is in the 4th step, since despite of module identification it is named as reconfiguration, as shown in Table 2.

The RMS present the characteristic of flexibility. It means that those systems are able to improve their capabilities in order to produce different mix and volumes of productions [22]. Specially in the last years, many articles have been studying intelligent manufacturing systems that connect the overall network in a smart factory [32][33][34].

Table 2. Process modular design steps.

#	Definition	Description
1	Cells Definition	Establishing the cluster of operations that composes a cell.
2	Cells interface development	Determining cells sequence, operations and their layout.
3	Cells platform design	Selecting cells that will be common for several products.
4	Configuration	Selecting and re-arranging cells according to the required changes.

The manufacturing system reconfiguration, also called process resequencing, has as input the identified product modules. In other words, here one needs to define which cells will be used and organized in the manufacturing process to produce the identified product modules and final products, with the purpose of achieving the best system configuration.

Until nowadays, few papers have evaluated the effectiveness of product and process modularity applied in an integrated manner to improve product variety and attain specific customer requirements [23]. It means that is yet most common finding papers considering the clusters of modules, which will compose the final product, as deterministic inputs of the process reconfiguration, as shown in Figure 3. Nevertheless, improving product variety and satisfying customer requirements increase the production process complexity, since there are many constraints simultaneously linked to the product and to the manufacturing process [35].

In order to deal with this complexity related to the manufacturing process, emerges the concept of Integrated Modular Design (IMD). The IMD aims to design, at the same time, the product and process, thus simultaneously identifying product modules and reconfiguring the manufacturing system to reduce cost and time, whilst improving product variety, efficiency and performance of the overall design process, operation and reconfiguration [23].

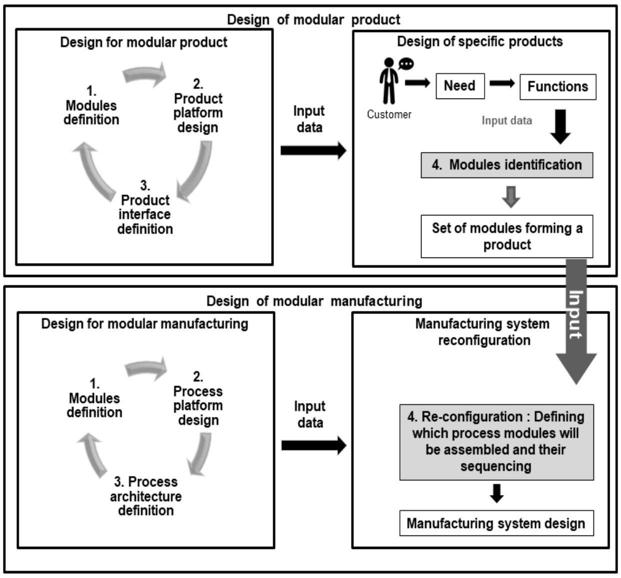

Fig. 3. *Modular design process for MC.*

4. RESULTS AND ANALYSIS

Figure 4 shows the number of scientific papers published over the years, evidencing that 2016 presented the highest number papers addressing modularity issues, between the years of 1997 and 09/2017.

It considers articles from journals and conferences. It does not mean that in the other periods, the number of publications addressing modularity was lower, but rather the focus on modularity issues were more pronounced. Moreover, relatively new research related terms were searched, such as “reconfigurable manufacturing systems” and “process modular design”. Thus it is a possible reason for the higher number of conference paper in relation to journal articles .

In general, one can observe that in the last years the number of publications has increased, which could be related to the appearance of Industry 4.0. Modularity and RMS are two main key technologies of Industry 4.0, since one of its objectives is to have a system capable to

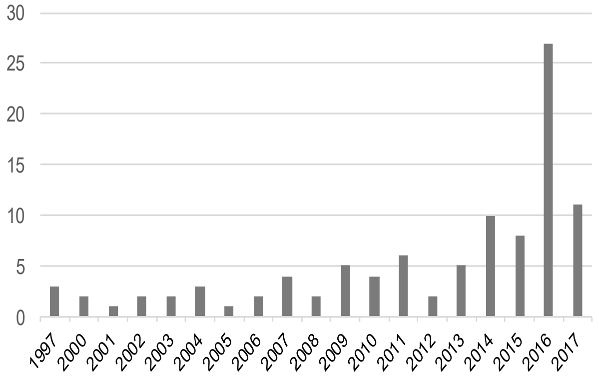

Fig. 4. *Evolution of publications over the years.*

Although the number of publications in 2017 is relatively high, when comparing with publications number over the years, in relation to 2016 the number has deeply decreased; which can be related to the fact that this paper's researches were conducted only until September 2017.

From Figure 2 is possible to conclude that there are many research works in product modular design while researches in process or manufacturing modular design are still moderate. A few number of research works have been addressing integrated product process modular design.

Figure 5 shows the number of publications per class over the years, in which is possible to see that since 2013 researches in integrated modular design, assembly systems design and reconfigurable manufacturing systems design have been increasing, although it is still moderate.

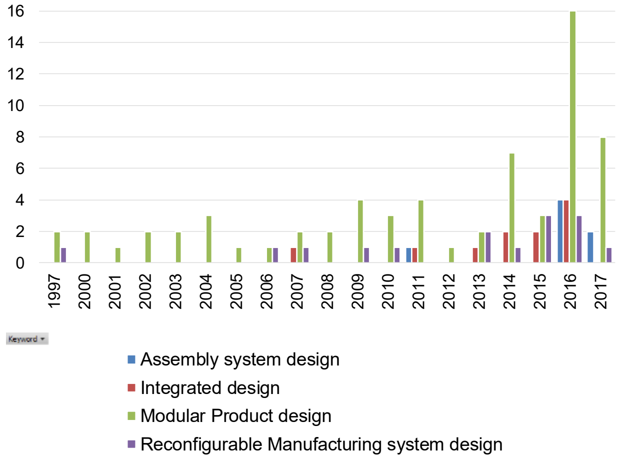

Fig. 5. *Number of publications over the year by subject.*

As shown in Figure 6, most papers were published in CIRP conferences proceedings via the journal Procedia CIRP, representing around 44% of the total publications. This shows the interest of this scientific community in modularity.

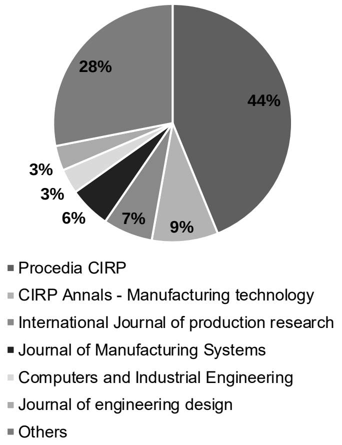

Fig. 6. *Number of publications by journal or conference.*

Reputed journals in Industrial Engineering, as International Journal of Production Research and Journal of Manufacturing Systems published papers concerning modularity, about 6 and 7%, respectively.

A large number of paper has been dealing with modular product design with different emphasis. Table 3 shows in which step of MPD, each research work is concerned.

As said before, the 1st step of MPD is interested in establishing the cluster of components that will compose a module. From literature review, one could perceive that researchers use different approaches to define their product modules, based on specific interests.

Table 3. *Different emphasis of Modular Product Design found in literature, based on the four design steps.*

Steps	Emphasis	Authors
1	Modules definition and modularity	[36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51]
2	Modules interface and product architecture	[52] [53] [54] [55] [56] [57] [58] [59] [60] [61]
3	Product platform	[19] [62] [63] [64] [65] [66] [67] [18] [68] [69] [70] [71] [72]
4	Modules identification and product configuration	[73] [74] [75] [76]

Generally, modules are defined in order to increase changeability and adaptability [37], or product variety management [39] [40]. Further, they are also defined to improve commonality between components [36] or to improve sustainability and market competitiveness [41] [43] [44].

After defining the product modules, the second step, consists on defining product architecture and, in parallel, establishing modules interfaces. There are different objectives used for defining product architecture. Some of the research works are focused on product variety or personalization to promote mass customization [52] [53] [56] [57] [58]. In addition, as product architecture is related to the layout, but also to the manner of each module will interact with others, one can find papers addressing this subject taking into account the assembling of manufacturing operations [53].

On the 3rd step, when developing product platforms, the authors aim at better managing and offering product variety [62] [63] and modules changeability/adaptability [64] [65]. This makes sense, since product platform means a collection of common elements, that can be shared among a range of products [77]; consequently, changeability and adaptability are important attributes of modules in order to promote product variety.

Since personalizing products affect directly the product platform, authors also have been addressing mass customization when dealing with this MPD step [67] [68]. In addition, Hanafy and ElMaraghy [19] investigated product platform configuration co-planned with assembly lines.

The last step in product modular design is based on choosing which modules will compose a specific product. The literature review shows that in the last years, research works have focused on module identification in order to promote mass customization and attain customer requirements [73] [74] [76]. However some works attempt to optimize their process of module identification with the intention to minimize the costs [75].

It is possible to observe that product variety and mass customization are issues considered in almost all steps of MPD. It makes sense, since modularity is a precursor of mass customization, by promoting a high production volume with high variety [78].

Another purpose of this literature review was to identify which type of tools and methods have been most used in the MPD and RMS. From Table 4, is possible to observe that Genetic Algorithms (GA) is the most applied method on MPD, followed by Design Structure Matrix (DSM) or general matrix approaches.

Table 4. *Main tools and methods used in Reconfigurable Manufacturing Systems (RSM) and Product Modular Design (MPD).*

Main Tools/Methods	**Authors**	
	RSM	**MPD**
DSM / Matrix	[79] [80] [81] [82]	[37] [40] [49] [54] [76] [83] [84]
Genetic Algorithms	[85] [86] [87] [88]	[36] [44] [68] [73] [89] [90] [91] [92] [93] [94]
Hybrid models	[95]	[52] [96]
Clustering analysis	[97] [80] [98] [99]	[49] [63] [83] [100]
Integer programming	[85] [97]	[19] [52] [101] [102] [97]
Heuristic algorithms	[103]	[48]
Fuzzy logic	-	[44] [45] [104]
Mathematical modelling	[81] [86] [105]	[53] [72] [74]
Axiomatic design	[106][107]	-
Others	[108][109] [110] [111][112][113] [114][115][116]	[43] [59] [75] [117] [118] [119]

GA can be used in module definition [36] [44], as well as to optimize product architecture [89] [90], or on the design of product platform and product family, in order to promote mass customization [68], [93], [94]. On the other hand, the DSM is usually applied on the first two steps of modular design, it means, on modules definition and architecture design [40] [49] [54] [84].

Integer programming (IP) is frequently applied in module identification [102] or to optimize platform configuration [19] [97]. Clustering Analysis (CA) is often used in module definition [83], module identification [49] or product platform design [63] [100]. Other methods found in literature review were based on the hybrid models, fuzzy logic, mathematical modelling, other heuristic methods, linear programming, etc.

A similar analysis was conducted for RMS (Table 4) in order to understand which types of methods and tools have been most used in literature review.

Similar to MPD, on RSM matrix approaches, CA and GA are frequently used. Sometimes, due to the complexity related to the manufacturing reconfiguration problems, the works conjugate two or more methods to attain their research objectives [80] [81] [85] [86].

Some research works have investigated how reconfiguration is influenced by management issues (i.e. line balancing, constraint of operations) [116], by resources and lead time [107] and optimal capacity [87]. The costs linked to the manufacturing reconfiguration were studied by Deif and Elmaraghy [114].

Unlike MPD, classifying the RMS papers by their emphasis on the steps of process modular design is still difficult, since this concept is more recent and most works are generally trying to better understand the factors influencing RMS.

Although many works address process modularity individually, without taking into account product modularity when reconfiguring the manufacturing system, it is important to integrate both concepts, since they are strongly related.

There are few works attempting to integrate both product and process modularity such as: effective management-support (i.e. departments coordination and supply chain) [120], co-evolution [85], concurrent product and supply chain design [121] flexibility and supplier failure risk [122], reconfiguration [123], [124] and productivity [125]; comparative analysis on product and manufacturing system design changeability [113].

Other works tried to investigate the relation between product and process variety [126], the integrated product and manufacturing system platform [106] as well as the co-platforming [80].

Furthermore, few research works proposed methods to optimize reconfigurable manufacturing systems taking into account the product design, in order to primally reduce production costs for mass customisation.

In general, these works tried to minimize costs related to configuration [97], to operation time [19] or the both [22]. Their optimization methods were based on variables related to product, such as: product family composition and product platforms, as well as to process variables, like machine allocation and group sequencing and layout formation.

Although these works address modular product and process in an integrated way, they still have some research limitations as shown on Table 5. Since these decision variables can affect significantly the results of an integrated optimization, one can deduce that more research in this area are necessary to improve the quality and accuracy of optimization models for an integrated approach of modular product and process for MC.

Table 5. *Optimization methods found in literature, which are based in an integrated approach.*

Methods	Co-platforming	Co-planning	Cellular manufacturing
Authors	[89]	[90]	[22]
Decision variables	Machine allocation as platform or non-platform and number of each machine required	Product family composition, product platform and stations required	Group layout formation and sequencing
Objective Function	Minimize the cost of reconfiguration	Minimize the cost of operation related to time	Minimize operation, and configuration costs of the entire system
Research limitations	Product modules is not considered	Reconfiguration is not considered	Process time is not considered
	Cost of layout reconfiguration is not considered	Manual tasks	Modules identification is not considered
	Operations sequence is not determined	Modules identification is not considered	

5. CONCLUSION

This review paper aimed to investigate how modular product and process have been treated in the last 20 years. From this literature review, one could observe that modular process design is still not fully mature, nor the integrated design of modular product and process.

Most of the reviewed works are singly focused on product modular design, more precisely on modularity, modules definition and product platform design. On the other hand, there are much less papers addressing process modularity and RMS.

In addition, there are still not many works addressing product and process modularity integrally. Further, some of them have tried to propose optimization methods to reduce production costs. However, no work have considered all the following simultaneously:

1. More than one module instance can satisfy customers' requirements.
2. Product and process modules simultaneously as decision variables.
3. Reconfiguration time optimization related to space, time and cost simultaneously.
4. Customers involvement implications on decision variables.

Therefore, future researches are necessary in order to fill these research gaps.

6. ACKNOWLEDGEMENT

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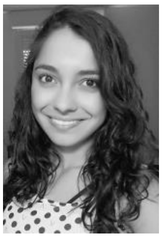

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