Modular design: Product design opportunities and a case analysis

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Abstract

In recent decades, modular design has been fully developed due to its important role in the current industrial evolution. The numerous advantages offered by its application to product design has made companies from different sectors opt for its use to solve particular needs. Many authors have studied modular design from a theoretical viewpoint, but it is necessary to learn about its application by studying real cases that allow us to understand what the object of its application is, the different methods used to obtain modular products and the results obtained in each case. Accordingly, we can know modular design's most characteristic features and benefits, the business of its application, what its evolution has been, and what path it is currently on as part of the current industrial evolution. To do this, a case study research is carried out, which is divided into two parts. The first consists of a bibliographic review that focused on the main authors who studied modular design and documented real cases of its application, especially at the beginning of modular design in industry. The second focused on investigating the current cases that have not been previously documented, which shows how modular design is currently applied and how it evolves.

Keywords: Design Methods · Modular Design · Product platform · Design opportunities · Case studies.

1 Introduction

Modular design began in the mid-1960s with modular production. In recent years, the competitive needs of companies in mass production sectors (e.g. automotive or industrial) have forced modular design to be implemented into companies to achieve greater competitiveness, higher supply diversity and more product portfolio options [1]. The present work is an analysis of modular design as an application in various productive sectors and as a future industrial design opportunity. Twenty-nine cases were analyzed in these sectors: industrial [2], transport [3], automotive [4], electronic

[5], consumer product [6], architecture [7] and furniture [8]. The study focused on three aspects: the design phase in which modular design is applied, the purpose of its application and the particularities of each case. This study confers a poorly extended design method visibility and high potential by providing real-life examples of its characteristics and benefits [9].

The first aspect to be studied is the phase as part of the design process, in which modular design is applied [10], where we find three different options. The first, when applied in the product life cycle, is where particular cases are identified in which companies have developed their own methodologies [11]. In this application we observe that there are links to the life cycle analysis from the environmental point of view, which has been a basic pillar in modular design for easy assembly, maintenance, replacement and disposal purposes [3]. The second option focuses on classic design process phases, such as the conceptual, design and development phases, with some conclusions about application opportunities in initial process phases. Finally, a particular case is analyzed, which is a research project applied as a previous phase to modular design [12]. Such research aims to determine which elements can make up architecture, platforms or product families in which to work on aspects such as interchangeability.

The second aspect to be studied is the objective that modular design aims by reflecting certain convergence toward module and product architecture definitions [15]. We observe that production flexibility [17], standardization [20], product platform generation [2] and model configuration [4] are the objectives found in the study. Other particular objectives tend to diverge with previous ones, and suggest decentralized production, multiple uses or mass customization.

Finally, the third aspect refers to the particularities of each case that allow a diverse definition of the modular design characteristics to be given. In both the bibliographic review and case analysis, lack of modular design characterization is observed along with specific applications, which generate particularities. However, a certain relationship is noted that can be established among the used model, the design phase and the desired characteristic to obtain a reference when applying modular design.

In the case study analysis, a reference is made to the various known methods and models [25], which are framed within methods of structural analysis [26], functional analysis [27] and matrix models [28].

Not every case has a clear reference to a model, but relationships can be established to define their theoretical framework. In this way, the study of cases also serves to reflect on current models and the need to implement new or more specific ones.

2 Method description

The main objective of this study focuses on research through a bibliographic review, and by analyzing real cases to which modularity has been applied throughout the product's life cycle phases.

As a result, we hope to find a series of cases that show which companies and sectors are related to modular design to know in which design phase it is applied, what purpose is set and what the particularities of each case are.

To achieve this, a bibliographic review that focused on various theses and articles, whose authors studied modular design, was carried out. Many research works focus on the initial applications in which modular design is first included, and show the need for its development [2]. At present, and given the many offered advantages, it is still developing. Some studies have conducted work on the documentation of real cases of applications in products as strategies or in platforms systems [3].

However, there are currently many cases that have not been previously documented and belong to sectors other than those already documented. For this reason, a search was made of new cases in the news, science magazines and on websites of various companies. A series of key sectors in which modular design had been applied due to the number of cases found in each one was identified.

Finally, two representative cases were included for these sectors: automotive, architecture, furniture, toys and electronics. The analyzed cases show the different ways of applying modular design by each company in the market, and describes what is being developed and what is the path that modular design is taking in relation to the future.

All the collected information was summarized in two tables, which provide basic information on the case (the product it affects, the company that applies it and the sector of the industry it belongs to) and a brief description of it, which includes the design phase in which it is applied, its purpose and particularities.

With the results already obtained in the form of a table, we conclude the study with the analysis of the results in the form of discussion and conclusions that deal directly with aspects related to modular design applications.

3 Results

In the bibliographic review, we found that 19 cases had been already documented and 10 recent cases to be studied, which means 29 cases to be analyzed from various sectors and companies.

The analysis of the results is included in Table 3. This table analyzes the relationship of all the 29 cases studied with the three identified aspects:

1. Design process phase. There are three different instances: Life Cycle Analysis (LCA). Design phase (Conceptual phase, which refers to a new idea that did not previously exist; Design phase, which refers to a solution that can be achieved without having to develop something new; Development phase, which refers to progress in a specific direction, as in technology, production, parts/components/modules of a product, etc.). Research.
2. Purpose of application as for configuration and platform. This aspect refers to the objective of the modular design in each case, such as obtaining new struc-

tures or product architectures, generation of modules, improvements in manufacturing machinery, etc.

3. Particularities or specific applications of each case. These particularities define the characteristics that differentiate them from the rest, which are related to modular design characteristics.

3.1 Documented cases

Table 1 shows a list of the 19 cases found in the bibliographic review documented in other research works with basic data and a summary of each one.

Table 1. Documented cases.

Case (product, company and industrial sector)	*Case summary*
Sperry-Sun Drilling Services [2] (Electronic sensors, Sperry-Sun Drilling Services, Machinery)	The company developed a range of products that allowed the incorporation of new technology. At the same time they were compatible and combinable with existing products. Because of this, the company opted for a strategy based on a modular product philosophy.
Crosfield Electronics [2] (Digital scanner, Crosfield Electronics, Electronics and printing)	The company created the Crosfield Product Life Cycle Process (CPLCP), a modular product development process in charge of defining modules in the conceptual phases and identifying the interactions that occurred between them.
Ford Motor Company [2] (Engines, Ford Motor Company, Automotive)	Ford restructured its business process worldwide under the name Ford 2000, which included the Ford Product Development System (FPDS) that allowed easy changes in the process through flexible production
British United Shoe Machinery [2] (Shoes Machinery, British Shoe Machinery, Machinery)	Given its expansion in the global market, the BUSM company went from highly complex functional manufacturing machines to simpler cheaper ones that required less skilled operators.
Modular system in truck manufacturing: The SAAB-SCANIA [4] (Scania trucks, SAAB, Automotive)	The case of Scania is one of the first modular design cases and its objective was to make modular trucks. Eight types of cabins were developed thanks to the use of standardized modules that allowed to make a new variant in a minimum time.
The case of Sony Walkman [5] (Walkman, Sony, Electronics)	This case is a classic example of success thanks to the use of modular platforms. Sony managed to create more product variants by adding modules to a platform, which made it very successful in the market.
Volkswagen platform strategy [11] (Automobile, Volkswagen, Automotive)	The multiple ranges of Volkswagen vehicles use product platforms to create product families. The company managed to develop a modular strategy that evolved over time, but always responded to market needs.
Modular German submarine [13] (Submarine, German army, Transport)	German submarines case (Submarine Type XXI) in which a submarine of a standard model was divided into several modules of longitudinal assembly to carry out decentralized production.
Locomotive Dash 2 Series	Locomotives Dash 2 presented a new electric driving system based on

[14] (Locomotive, General Motors, Transport)	separable modules that allowed defective modules to be replaced without having to take the entire locomotive to repair.
Merima Ltd [8] (Logistic organization, Merima Ltd., furniture)	Merima Ltd applied modularity to the design and logistics of a restaurant to be installed on a ship. The restaurant was built on the facilities, dismantled, transported in modules and delivered with assembly instructions.
Tunnel drilling rig [3] (Drilling rig for tunnels, Tamrock and Jumbo, Machinery)	This is a research project in which the use of platforms for different product families of the Tamrock and Jumbo drilling brands was analyze, and offered an analysis on how to apply greater modularization according to their functions.
Diesel locomotive [3] (Locomotive, Valmet, Transport)	The Valmet locomotive was designed and manufactured with a modular structure, which allowed it to be modified and have multiple uses. This modularity is based on assembly and facilitated maintenance in general, with a saving of 30%.
Passenger ship [3] (Passenger ship, Finnish financing agency for technology, Transport)	It is a project that seeks to improve the efficiency of ship delivery through modularity and flexible standardization to discover the division of the ship based on modules to develop modular ships.
Safe-deposit box [3] (Safe box, Kaso Ltd., Machinery)	Families of safety deposit box products were examined to discover opportunities to move from the production of standard models to the production of configurable products.
Machine tool [3] (Machine tool / Twin-Mill, Fastems Ltd., Machinery)	The company undertook a modular development project whose objective was to define the structure of a Twin-Mill machine by finding out where to implement a division of modules based on their functions, and creating a range of configurable products.
Ambulance [3] (Ambulance, Profile Vehicles Ltd., Transport)	The functional structure of an ambulance was evaluated and lists of its main functions were made. Thus the opportunities to create a modular structure based on the functional structure were examined.
Forestry machine [3] (Forestry machine, Ponsse Ltd., Machinery)	The Ponsse company created modules that did not only focus on assembly, but also on functionality. Several modules were sets of parts located around the machine that could not be assembled separately.
Volvo trucks [15] (Configurables trucks, Volvo, Automotive)	Volvo developed a configuration system for its range of trucks as part of the CATER project (2006), whose objective was to create business networks and mass customization in the automotive industry.
Micro Compact Car (MCC) [16] (SMART, Micro Compact Car (Daimler), Automotive)	MCC established diverse relationships among product family development processes, product architectures and a multi-rand modular organization to create a collaborative modular development project organization.

3.2 Recent cases

The previous section shows that more than half the previously documented cases corresponded to the transport or automotive sector, followed by the machinery development sector. At present, more industry sectors that are closely related to modular design have not yet been documented. Table 2 shows 10 recent cases that correspond to the following sectors: automotive, architecture, furniture, toys and electronics.

Table 2. Recent cases.

Case (product, company and industrial sector)	*Case summary*
PSA (Peugeot-Citroën) [17] (Platform for several compact models, PSA Group, Automotive)	PSA seeks to manufacture most of their compact models of the four brands on the same product platform. The company has two global platforms that are compatible with the industrial resources launched in the The Factory of the Future programm: the CMP (Common Modular Platform) and the EMP2 (Efficient Modular Platform).
Renault Mégane [18] (Renault Mégane, Renault, Automotive)	The latest Renault Mégane's model contains a modular interior that is one of the most spacious and adaptable models in its segment. It offers an interior with a range of options that adapt to the user's needs.
BoKlok [19] (BoKlok, IKEA, Architecture)	BoKlok is a housing concept whose objective is to build blocks of flats and houses for low-economy people. IKEA developed modular houses of a few square meters by making them spacious and affordable at the same time.
Blokable [7] (Blokable, Amazon, Architecture)	Blokable develops prefabricated building modules (Bloks) in a wide range of sizes and configurations to provide living spaces, common areas and services that meet the specific needs of each project type.
IKEA products (BESTÅ, shelves and children's furniture) [20] (Products IKEA, IKEA, Furniture)	IKEA has several examples of applying modular design in its products: the BESTÅ furniture, a set of modules with standardized measurements; shelves of different sizes and colors; and children's storage furniture, to name but a few.
Ori Systems [21] (Ori Systems, MIT, Furniture)	It is scalable modular furniture that changes shape to create more efficient spaces. Its goal is to make life more affordable, productive and enjoyable for users. This versatile piece of furniture confers different rooms space, such as a room or study.
Mindstorms [6] (Mindstorms, LEGO, Toys)	It is a line of robotic toys that works with the combination of modular pieces and the programming of actions interactively. Its use is based on the construction of integrated models with computer-controlled electromechanical parts.
Meccano [22] (Meccano, Meccano, Toys)	Meccano has upgraded its building model system by assembling modular parts, such as plates, angle beams, wheels, axles and gears, and plastic parts that are connected together by nuts, bolts and fixing screws.
GoldieBlox [23] (GoldieBlox, GoldieBlox, Toys)	GoldieBlox offers toys that are sold in kits, and that incorporate modular pieces for structure construction. Thus, these toys introduce engineering concepts through storytelling and construction.
Modular Smartphone [24] (Various products, various companies, electronics)	It is a smart phone manufactured with modules that can be updated to reduce electronic waste, repair costs and increase user comfort. The most important component is the main board, to which the modules are connected (processor, battery, camera, etc.). Some brands, such as Motorola, LG or Google, have already worked in this field.

In Table 3 the 29 cases described in Tables 1 and 2 can be analyzed, and an analysis is done by taking the three initially described aspects, and observing in the summary column what particularities are more remarkable in each aspect, and the details of each aspect in the corresponding column for each case. The results of Table 3 are discussed in Section 4.

Table 3. Case analysis.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Σ
1st Aspect	LCA		x																											x	2
	Concept	x	x	x	x	x	x	x	x	x	x	x		x	x		x						x	x							15
	Design	x		x	x	x	x	x	x	x	x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	25
	Development	x		x	x	x	x	x	x	x	x	x		x		x				x	x						x			x	15
	Research											x																			1
2nd Aspect	Configuration					x																									1
	Platform	x		x								x									x									4
	Family											x			x																2
	Architecture / Structure						x	x								x	x	x	x	x											7
	Block / Module								x	x	x			x									x	x	x	x	x	x	x	x	12
	Own method		x	x																											2
3rd Aspect	Interface / Interaction		x																								x	x			3
	Maintenance									x			x																	x	3
	Compatible	x																													1
	Combinable	x																													1
	Repair									x																				x	2
	Product Flexibility			x										x																	2
	Production Flexibility			x																	x										2
	Decentralized Product								x		x																				2
	Simplicity				x																										1
	Assembly												x																		1
	Economy				x																		x	x							3
	Functionality						x	x				x	x			x	x	x													7
	Standardization					x																			x						2
	Logistics																														0
	Variability																														0
	Time economy					x																									1
	Configurable						x								x							x		x							4
	Personalization																					x			x						2
	Market																			x											1
	Integration																										x	x			2
	User Narrative																												x		1

4 Discussion

In a globalized and competitive market, modular design has proven a useful design tool to face this competitiveness through higher supply diversity and a better response to changing market demands, while making the manufacturing process more adaptive to change. The analyzed cases prove the usefulness of modular design and the advantages of its application to industrial development in last decades. Nowadays its main objective is the application of methodologies in which the design phase prevails, the definition of modules to seek functionality and the possibility of generating configurations. Therefore, modular design offers a development opportunity due to the context in which it is found with the variables directly related to its objectives; e.g., a competitive market, fewer resources, more demands and the latent need for product

customization. In economics and business, the modularity of products, services and processes is a key factor in technological, economic and social development.

The analysis of the most recent cases reflects the importance of modularity as a future industrial design opportunity in the current industrial evolution. These cases use modular design as a tool to face current challenges, such as the needs of customers and companies, new technologies like Industry 4.0, the standardization of design entities and agile manufacturing. In addition, the growing demand for customized products is pushing companies to adopt the principle of modularization in their product design and development phases, which offers them the advantage of creating customized products or services easily and economically. As shown in Table 3, no registered case's objective was product personalization, while there are two recent cases that did [18] [20]. This is why modular design development can be established as a milestone in the history of industrial production, where modularity can become a great future challenge.

By analyzing the studied cases, three design process points were detected in which modular design was applied. The first is its application in the product life cycle, where modularity allows it to be extended by adapting it to new requirements and its evolution by incorporating new features. This means that modular design fits an environmental context with a strong link to the circular economy, and modular design can bring major improvements by allowing the development of reusable, repairable and updatable characteristics. At this point, an opportunity is detected to develop a line of modular design that addresses the environment given the scarcity of cases that focus on this aspect (only two cases). The second point refers to classic design process phases. In this case, an opportunity is identified to apply modular design to the initial conceptualization phases with new design methodologies as cases are scarce. The third point is the opportunity to introduce research into modular design methods. This situation may vary the aim of modular design by introducing the search for new requirements before the process starts.

The second aspect is related to the blocks or modules that can shape a product's architecture, which are determined to create a platform that gives rise to a family of products by bearing in mind the interchangeability of components. In line with this, it is observed that while the documented cases focus on product architecture, most recent cases center on the module (Table 3).

The characteristics of the modular design and the third aspect are closely linked to its benefits. These characteristics are specific and particular to each case, and modular design application to the product design and development increases the final product's level of modularity by providing traits that offer significant advantages during its life cycle. Differences in the use of these characteristics exist between documented cases and recent cases. While documented cases opt for functionality, product decentralization or product flexibility, the most recent cases opt for those such as interaction, economy, personalization or integration (Table 3). By connecting independent modules on a single product platform, modular design makes the product variable and configurable. Many companies use this fact to lead to characteristics such as adaptability, and the ability to mutate according to the needs of users and the environment; personalization both before manufacturing the product (automotive) and during its life

cycle (modular smartphone); multifunctionality, integrating multiple functionalities through modules; and flexibility, especially regarding the manufacture of the product. These characteristics arise thanks to the standardization and connectivity of modules, which render them interchangeable, reusable and updatable which, in turn, improves the economy of scale.

5 Conclusions

The study of documented cases of modular design applications allowed us to know the reasons why it was first used in industry to thus understand the bases that established it and its subsequent development in industries of various sectors. Otherwise, the study of recent cases shows the diverse forms and purposes of applying modular design to the current economy, and the place it occupies in the present industrial evolution. At the same time, the results of this study reveal that there are numerous sectors in which modular design is not currently used, but where a potential application will possibly exist if it continues to develop. Table 3 shows the need to increase the efforts being made in many aspects, such as configuration, compatibility, simplicity or variability, as part of the current industrial evolution.

As shown in the results, some sectors whose development and evolution from the past to the present are greater include: automotive, with companies such as Ford or Volkswagen; architecture, BoKlok of IKEA; furniture, Ori Systems developed by the MIT; electronic, Sony Walkman; toy maker, Mind Storms of LEGO; computers, with hardware and software development; mechanics, especially as regards machinery design. The use of modular design in some of these sectors has been so influential that it has given rise to new design concepts such as *kit car*, *kit house* or *modular smartphone*. However, there are several sectors in which modularity has not yet been incorporated into product design, such us the food, textile or sanitary sectors. This means that there is a large niche market where modular design can be incorporated into if it continues to develop in the near future.

Our results show that there are numerous methodologies and models, some theoretical and some particular to each company, that allow modularity to be applied to product design. As shown in the case summary in Table 1, the effectiveness and reiteration of its application results in a series of models that have already been consolidated and validated for decades, and are classified into: methods of structural analysis, functional analysis and models based on matrices. Some of these models are more recent and offer a more limited application in real cases, which means they are currently in an experimentation and development state. However, it has been detected that its use in conceptual development phases is lacking in most methods, which represents an excellent opportunity to develop a new method.

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