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Matheus Bólico Lima
Federal University of Paraná
Flavio Issao Kubota (flavio.kubota@ufpr.br)
Federal University of Paraná

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A Modular product design framework for the home appliance industry

Matheus Bólico Lima[1], Flávio Issao Kubota[2*]

[1] *Department of Mechanical Engineering, Federal University of Paraná, Polytechnic Center, Post Code 19011, Curitiba, PR, Brazil*

[2] *Department of Mechanical Engineering, Federal University of Paraná, Polytechnic Center, Post Code 19011, Curitiba, PR, Brazil * Corresponding author – ORCID iD: https://orcid.org/0000-0003-3743-9466*

E-mail addresses: mbolicolima@gmail.com, flavio.kubota@ufpr.br

Abstract

Methodologies that optimize product development are becoming increasingly important due to global competition. Additionally, customers have been more demanding in terms of product quality, also requiring more environmentally friendly goods and services. In order to accomplish with these goals, this study builds a product modularization framework for developing new products. We developed our protocol based on the Modular Function Deployment (MFD) and the Product Line Commonality Index (PCI). We obtained the modules after applying MFD and compared them with an actual product developed by a home appliance organization, to ensure validity in both theory and practice. We chose the hinge module to apply PCI, finding a significant potential to communize the component. A careful analysis of MFD and PCI outcomes in the product development process may increase modularization efficiency and bring pertinent information for product architecture decisions and strategies. However, it is noteworthy that a market analysis is needed before communizing components. On one hand, companies may reduce development and manufacturing costs through part commonality. On the other hand, there may be market rejection due to product design and architecture changes.

Keywords

Modularization; Modularity; Home Appliance Industry; Refrigerators; Modular Function Deployment; Product Line Commonality Index.

1. Introduction

With the constant growth of competitiveness worldwide, companies must adapt to new dynamics to meet customer expectations and requirements. Pressured by more effective results in market products and by shorter launch times, product engineering teams face several challenges in the development of new products. These include the rapid advancement of technology, globalization, and changing customer needs [1]. Furthermore, there is a continuous demand for cost reduction and quality improvement. Technology has evolved faster, making it increasingly complex and challenging to develop new solutions and leading companies to deal with greater complexity and continuously changing environments. Due to this complexity and challenges, methodologies and metrics that optimize product development are becoming increasingly valuable.

Product modularity has been applied to deal with these growing challenges. It is a concept based on splitting a product into independent and, generally, smaller subsystems [2]. The main goals of modularity are (i) facilitating the management of products and production processes and (ii) enabling new product development activities in parallel. These would allow the production of diversified products through the combination of independently developed subsystems that, when coupled, work as a whole [3, 4]. Companies have applied modularity to adapt to dynamic markets, where sudden demand changes by customers and a high rate of component and product technological changes frequently occur [5]. Modularization is a vital strategy to reconfigurable systems that can adjust to sudden demand changes and provide quick production launch of new products, taking advantage of promising market opportunities, thus contributing to a better responsiveness to product development systems [5]. Accordingly, multiple modularization methods are available to support the overly complex task of identifying module candidates in product architecture [6].

Modular product architecture is a strategic means to deliver external variety and internal commonality, and has been explored in several areas, such as the electronics industry, photographic cameras, computers, automotive, cyber-physical production systems, and the home appliance industry [6,7,8]. The Waste from Electrical and Electronic Equipment (WEEE) encompasses a wide variety of products that range from large household appliances, such as washing machines, to information and communication technologies such as computers or mobile phones [9]. Household appliances such as refrigerators, washing machines, and dishwashers stress the environment throughout their life cycle. Modularity is one of the design practices that may contribute to reducing such environmental impact by, for instance, simplifying remanufacturing activities directly in the design phase through modular structures and standard components [10]. This concept can support engineers in developing more sustainable product architecture, being environmentally friendly, and meeting governmental regulations when pertinent [11].

Modular product architecture plays a vital role in developing sustainable products; the primary goal of sustainability in product design is to develop solutions that adequately balance the private interests of companies and social and environmental concerns [12]. Based on [13]'s study, [14] built a systematization of modular product design within the refrigeration industry, considering the Modular Function Deployment (MFD) method. It sought to develop a reference model so that this industry could enjoy the benefits of modular product design. According to [14] framework, modularity should extend to the product structure itself so that producers can identify modulable systems and subsystems that could benefit from this type of methodology.

Thus, identifying systems and subsystems that can be modularized may generate benefits for companies within this segment. Furthermore, given the sustainability challenges, developing systematic and objective processes to identify modularizable systems can represent significant opportunities to apply commonality and standardization in products, thus obtaining potential cost reduction and process improvement. Additionally, "any significant novelty in product architecture is interesting from both an academic and an applied approach" [15, p. 707]. Based on those arguments, we state the following research question: "*How do companies may organize themselves to develop modular products with increased quality and reduced costs and, at the same time, ensuring sustainable requirements and environmental regulations?*"

Hence, this paper develops a product modularization protocol to obtain a higher component commonality degree and the subsequent possibility of reducing costs, environmental impact and increasing profitability and compliance with environmental regulations. Our goal with this modularization protocol is to support firms that plan to modularize their products matching quality and environmental requirements. Next, section 2 presents the literature review that supported our paper. Section 3 details the research methods and procedures. Section 4 presents the results of our modularization protocol. Next, section 5 discusses the findings of the study. Lastly, section 6 draws the main concluding remarks, limitations, and future research possibilities.

2. Literature review

This section presents the literature review carried out to provide a theoretical foundation for the paper. We subdivided this section into (i) modular product architecture, (ii) modular product design methods, (iii) Modular Function Deployment (MFD), and (iv) Product Line Commonality Index (PCI).

2.1. Modular product architecture

The architecture of a product is the scheme that arranges the functional elements of the product in physical parts and defines how these parts interact through interfaces [16]. Such decisions about this architecture will influence the entire project management and organization. At this stage of the project, we divide the product into three categories: systems, subsystems, and components. We can classify the architecture of a product as integral or modular. An integral architecture consists of distributing product functions across various sets of components. The interactions between these components are poorly defined. This type of architecture is generally employed for high design performance since it can combine functions in a few components to optimize specific performance parameters. However, design modification may require an extensive redesign of the product, affecting different functions [16]. Integral architecture is typically used when customers have similar needs and desires. If product components demand updating simultaneously, there is little motivation to go modular and little need to adopt a modular design to provide variety [17].

On the other hand, modular product design consists of designing a product made up of modules [18]. Each module performs a particular product function with little or no interaction with other modules. If there is interaction, it must be clearly defined. A module can be seen as a black box; except for the restriction that its output must comply with the general rules or specifications of the overall system, the subsystem is entirely free in its design [19]. If design changes are required in modular architecture, organizations may carry it out in one module without modifying others. Also, modules can be designed independently of each other [16]. Modular product architecture is commonly adopted when customers have different needs and demands (e.g., style preferences); Another important reason for adopting modularity is that it has the potential to ease cost-effective customization and thus increase product variants that can be offered at any given point in time [17].

A modular structure facilitates coordination and helps to (i) organize interdependencies [20], and (ii) manage complexity [21]. However, too high modularity may have downside effects; for instance, it encourages specialization within modules, thus creating barriers to collaboration; therefore, modularity is often counterbalanced by integration [21]. Nevertheless, the modular design has been increasingly introduced into household appliances to maximize the number of standardized components [22]. It can also broaden the innovation concept by improving sustainability features, contributing to the product's environmental performance [22, 23], and mitigating environmental burdens [22]. Hence, product modularity is supposed to offer environmental benefits throughout the product life cycle [12]. After developing the product architecture, we must refine the analysis to detail and define critical aspects observed throughout the product life cycle. These aspects include operation, manufacturing, assembly, performance, quality, costs, use, and disposal [12,22]. This information enables us to obtain better alternatives for component manufacturing and product assembly. A proper analysis of the aspects listed above will prevent or minimize risks in product development, avoid rework, enable satisfactory product performance, and reduce costs and lead time [16].

2.2. Modular product design methods

Modularity may not necessarily lead to superior environmental performance because extra transportation of customized parts may be needed, as related by [22]. In other words, the costs of unique and customized components are higher than the costs of standardized ones. [14] argues that production must deal with specific processes: there is a need for specialized machines and tools; quality control is sophisticated, and there may be a need for a layout change. Meeting customer demands requires significant investment [14], and modular design methods may support this multifaceted scenario.

Modularity is a powerful strategy proven helpful in many areas that deal with complex systems. It is used for different functional purposes such as product design, production, and use [24]. Modular product architectures are also considered potential sources of enhanced strategic flexibility for firms that face dynamic market environments [25]. [26] developed an extensive systematic review of the main modularization methods in the literature. The authors aimed to select the method that best suits the needs of those who will perform modularization according to the specific product to be developed. Table 1 shows the principal methods found in the traditional literature, as well as their primary objectives.

Table 1 – Main modularization methods found in the literature

Methods	Criteria
Design Structure Matrix (DSM) [27]	Finding architectural alternatives to optimize the resulting design quality and facilitate the coordination demands required when subsystems interact.
Modular Function Deployment (MFD) [28]	Achieving a modularization that meets the company's improvements, supporting the selection of guidelines and strengthening the company's ability to confront expansions and future demands.
Heuristic Model (HM) [29]	Providing a systematic approach to identify the modules of a product from a functional model.
Design for Variety (DfV) [30]	Developing a decoupled architecture that requires less effort to develop future products.
House of Modular Enhancement (HOME) [31]	Developing a modular design method to address life cycle issues in the design phase.
Fuzzy Logic Based (FLB) [32]	Optimizing the potential module performance while modularizing product architecture during the concept development phase.

Modularization methods have some similarities. Therefore, we must analyze those methods by following some criteria to select the most appropriate one then. [33] present three critical steps for product modularization: (i) product decomposition into parts, (ii) integration of these parts into modules and (iii) evaluation of the resulting design. Similarly, [34] argues that modularization methods are based on three steps: decomposition, decoupling of interfaces, and recombination of parts. All analyzed methods go through the decomposing and integrating process; however, they use different tools and strategies. The evaluation step, although relevant, was not present in all the assessed methods. The following subsections present the phases (decomposition, integration, and assessment/evaluation) of this process, emphasizing the MFD method.

2.2.1. Decomposition phase

One of the most common approaches among the methods is the functional decomposition of products, also called functional modeling. Functional decomposition is the process of unfolding the product's overall function into easier-to-solve subfunctions [29]. These subfunctions provide a detailed description of what the product should do. At this stage, one of the most critical aspects of method analysis is the existence of different degrees and types of decomposition. The methods we analyzed include functional decomposition (Heuristic), functional and physical decomposition (DSM, HOME, and FLB), and physical decomposition into technical solutions (MFD) and components (DfV). The higher the degree of decomposition, the easier it is to find the relationships between functions and physical parts, but the harder it is to integrate these parts [33]. Therefore, we must conduct product decomposition at a level of detail similar to the one we desire for product architecture.

2.2.2. Integration phase

It is the stage in which the modularization process occurs. The elements identified in the decomposition phase need to be grouped to form the modules. According to the literature, matrices are one of the most common forms used for the integration phase. The MFD method performs modularization through the Module Identification Matrix (MIM). Each technical solution of the product is scored according to modularization guidelines, similar to Quality Function Deployment (QFD). These scores are as follows: 5 (strong relationship), 3 (medium relationship), 1 (weak relationship), and 0 (nonexistent relationship). Modularization guidelines involve companies' reasons to modularize their products (e.g., upgrading, recycling, variety, maintenance). After completing the matrix, we obtain the solutions, where the highest scoring solutions are candidates to become modules. Low scoring solutions have no significant reason to become modules and can be integrated with other solutions according to indications of similarity pointed out in the MIM [26].

2.2.3. Assessment phase

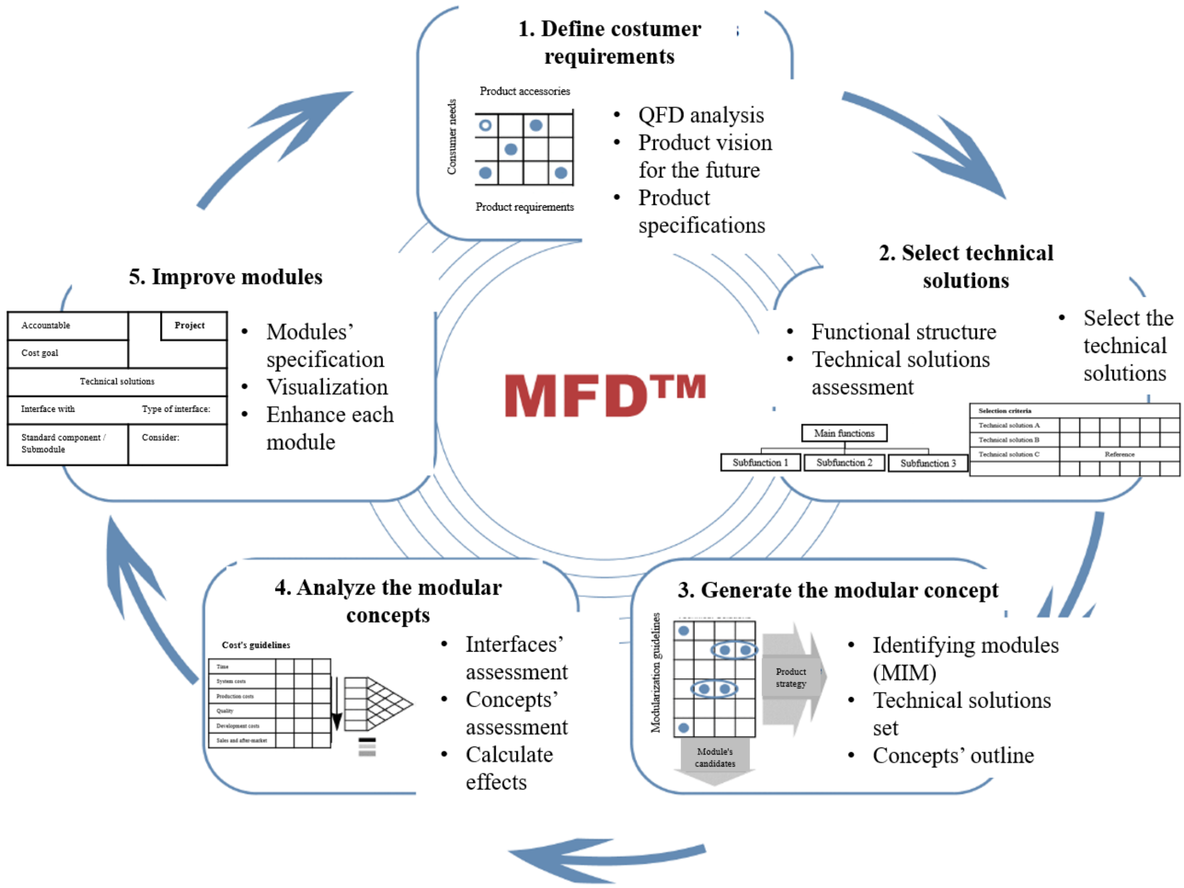
Among the analyzed methods, only MFD and HOME have an evaluation step. However, there is no formal procedure to follow in the HOME method: modules are analyzed according to their groupings to verify their feasibility. In the MFD method, there are two evaluation steps: interface analysis and intramodular enhancement. The first one consists of the interface analysis between the modules that, besides clarifying the relationships between the modules identified in the MIM matrix, verify the system as a whole. The other step concerns intramodular optimization [26]. The other methods do not have formal procedures for design assessment resulting from the integration phase. However, all methods suggest assessing the resulting design and, if necessary, revising it [26].

Hence, after analyzing the modularization methods present in the literature, we chose the MFD because it is the method that covers the three phases (decomposition, integration, and assessment) with robust and formal procedures. Therefore, the following section presents a deep theoretical background regarding MFD.

2.3. Modular Function Deployment (MFD)

Modular Function Deployment is a method applied to single products or product families and consists of five steps [13,35], as shown in Figure 1: (i) defining customer requirements, (ii) selecting technical solutions, (iii) generating concepts, (iv) analyzing concepts, and (v) enhancing each module.

Figure 1 – MFD™ Steps [14]



Step 1 – Defining customer requirements: listing customer requirements and defining measurable and controllable product properties. Subsequently, we correlate those properties through the Quality House Matrix [36]. Elements are scored 0 (low), 1, 3, or 9 (high), depending on how project ownership impacts customer needs. Additionally, we assign a value for each consumer requirement, from 1 (least important) to 5 (most important). The total value of each column is the sum of the multiplication between the value assigned in each row and the respective criterion value. The objectives of the first step of the MFD method are: (i) defining the market segment; (ii) guiding market decisions; (iii) establishing and prioritizing consumer requirements by market segments; and (iv) developing design requirements [14]. Figure 2 illustrates the simplified QFD matrix.

Figure 2 – Simplified QFD Matrix (Adapted from [11])

How? / What?	Modularity	Product Properties											Criteria weight
Customer Requirements	●				○								5
		●		●									3
						●							2
													1
		○		▽							▽		4
	●							●					5
						●							2
	●		▽										3
											▽		1
													1
													4
Total													
Priority													

● Strong relationship (5) ○ Medium relationship (5) ▽ Weak relationship (1)

Step 2 – Selecting Technical Solutions: decomposing the product into Technical Solutions (TS) to meet Product Properties (PP) and describing how each TS impacts PP performance. We use the Design Property Matrix (DPM) to conduct this correlation, as shown in Figure 3. We can build several technical solutions for the same PP; in this case, we must use techniques to decide which one to use. In summary, the objectives of the second step of the MFD method are: (i) analyzing product functions; (ii) suggesting technical solutions to fulfill functions; and (iii) connecting technical solutions with product properties at DPM [14].

Figure 3 – Example of a generic DPM (Adapted from [28])

Technical Solutions	Modularity	Product Req. 2	Product Req. 3	Product Req. 4	Product Req. 5	Product Req. 6	Product Req. 7	Product Req. 8	Product Req. 9	Product Req. 10	Product Req. 11	Product Req. 12	Scoring
Technical Solution 1													
Technical Solution 2		●								▽			
Technical Solution 3		●			○								
Technical Solution 4							▽						
Technical Solution 5		○			○								
Technical Solution 6													
Technical Solution 7						▽							
Technical Solution 8						●					▽		
Technical Solution 9													
Technical Solution 10	●												
QFD Result													

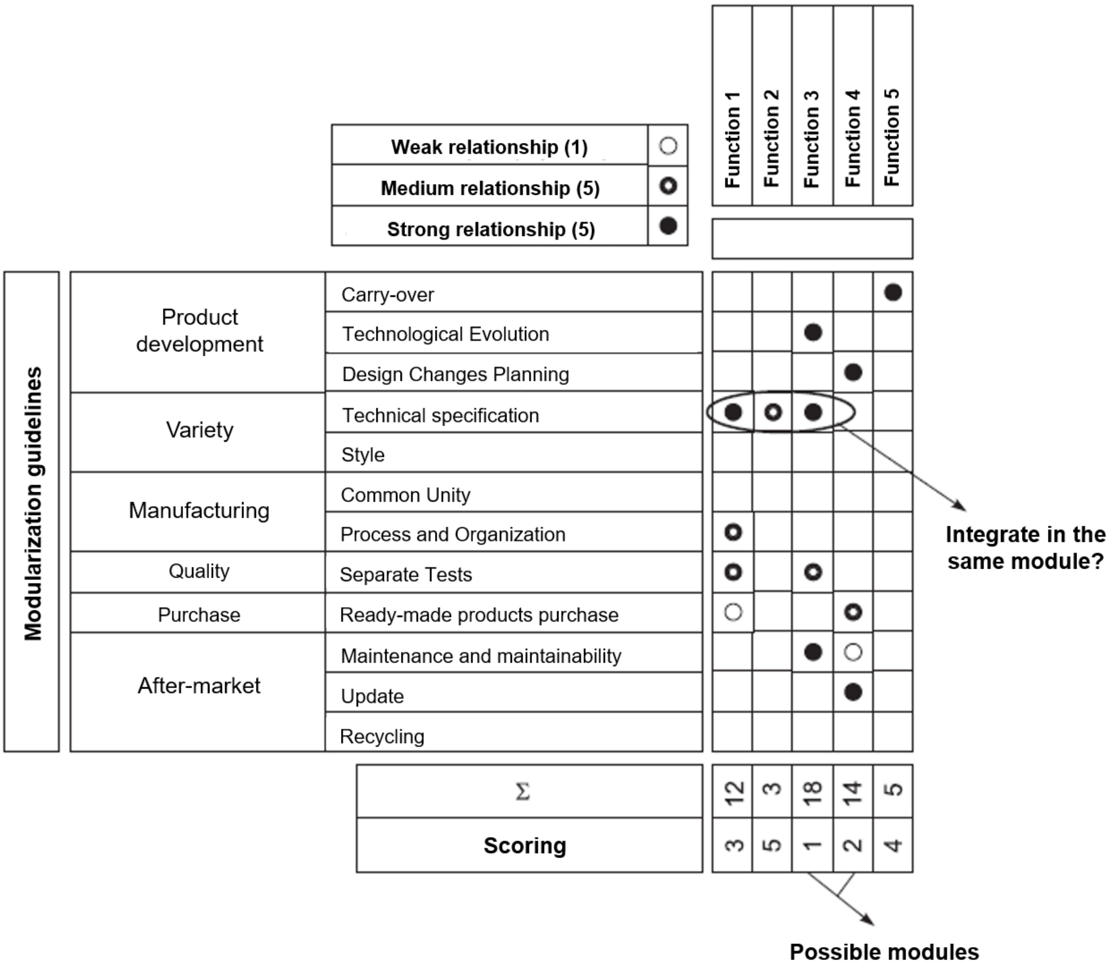
● Strong relationship (5) ○ Medium relationship (5) ▽ Weak relationship (1)

Step 3 – Generating the modular concept: correlating technical solutions (TS) with the company's objectives using modularization guidelines (Module Drivers – MD – Table 2) according to their importance within the project. We conduct this correlation through the modular interface matrix (IM), assigning the values 0 (weakest relationship), 1, 3, and 5 (strongest relationship) to the relationships. [13] also recommends using statistical software to enter DPM and MIM matrices' values and generate a hierarchical branch (dendrogram) to indicate the modules. "A dendrogram is a representation map of affinities between components showing the 'closer' components being putting together for merging and integration” [37, p. 252]. Thus, the objectives of the third step of the MFD method are: defining the modules with the help of the modularization guidelines and technical solutions obtained in the second step; generating the modular concept using the Module Identification Matrix (MIM – Figure 4); and outlining the modular concept [14].

Table 2 – Modularization Guidelines [16]

Product development	Carry-over	A function can be a separate module where the current technological solution can be taken to a new generation/family of machines.
	Technological evolution	A function can be a single module if it has a technology that is overcome during product life cycle.
	Planning for design changes	A function can be a separate module if it has characteristics that will be changed according to a plan.
Variety	Technical specification	Changes can be concentrated to achieve variants in a module.
	Style	A function can be a separate module if influenced by trends and fashions so that the shapes or colors must be changed.
Manufacturing	Common Unity	A function can be separated into a module if it has the same physical solution in all variants.
	Process and organization	Reasons for separating a function in a module: - Having a specific task in a group. - Fitting the company's technological knowledge. - Having a pedagogical setup. - Having an assembly time that differs significantly from that of other modules.
Quality	Separate tests	A function can be separated into a module when this function can be tested separately.
Purchase	Purchase of ready-made products	The function can be treated as a black box because of reduced logistical costs.
Aftermarket	Maintenance and maintainability	Maintenance and repairs can be made easier if a function looks good in a separate module.
	Updating	If necessary, it can be facilitated if the function to be updated is a module.
	Recycling	It can be advantageous for concentrating polluting or recyclable materials in the same module or in separate modules.

Figure 4 – MIM Matrix [16]



Step 4 – Analyzing the modular concept: This is the moment to define the interaction and the interface relationship between the generated modules. Modules must have standardized interfaces and interactions, as these definitions are a *sine qua non* condition for the success of the modular design. We use the Interface Matrix (IM – Figure 5) for this step, listing the modules obtained according to their assembly sequence and correlating them with each other based on the interface classification of [13]. The fourth step of the MFD method consists of identifying, defining, and describing module interfaces and indicating the Product Management Map (PMM). The PMM combines the QFD matrix with the DPM, MIM, and IM matrices; this map gives the project team an overview of the modularization process. Figure 6 shows the representation of a PMM.

Figure 5 – Interface Matrix (Adapted from [13])

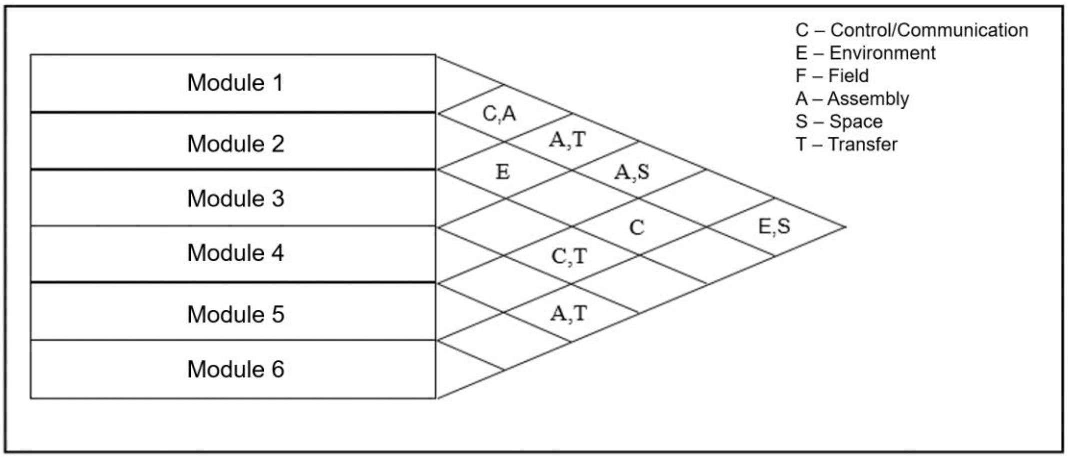
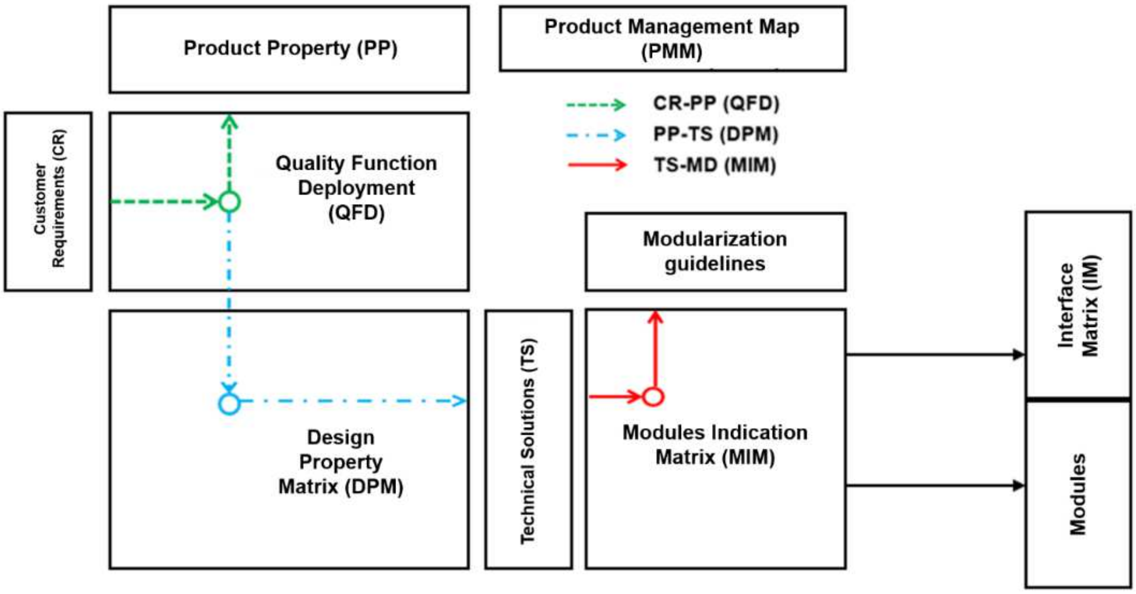


Figure 6 – PMM (Adapted from [38])



Step 5 – Improving Modules: We list all the relevant information to define the modules, such as customer requirements, product ownership, technical solutions, company strategies, and interface type. That information will offer significant support to develop and design the modules, being used as a communication document with other companies [38]. The objectives of this MFD method step are: (i) specifying and describing the modules, (ii) performing technical analysis, and (iii) planning the implementation of the modular concept. [13] establishes some prerequisites for applying the MFD method: (i) knowing consumer and market requirements, (ii) understanding short- and long-term business strategy of existing projects, and (iii) future development plans. Furthermore, the project team and functional area specialists who will support the project should be aware of modularity concepts.

2.4. Product Line Commonality Index (PCI)

Each product has a unique set of functions within a given product family to appeal to targeted market segments. This feature set may include certain unique features or a unique combination of features that are different from those offered in products from the same family. However, there will be specific basic functions that all products within a product family share (the same functions justify the term *product family*). All physical components and subsets considered as "basic functions" common to two or more products within a family must have the same physical characteristics. These components are called non-differentiators. A component does not add a particular function concerning another product of the same family [39].

As attempts are made to compare different manufacturers in their efforts to standardize components between models, the ideal would be to have an objective and accurate measure to assess differences in product design strategies. A simple metric would be the percentage of standard components in a product family. However, this metric would ignore the degree of differentiation in a product family, penalizing products with a broader combination of characteristics [39]. The degree to which a family's products differ is a strategic decision. Thus, we must look for a metric that penalizes only differences that should not exist, i.e., be shared. [39] define the PCI metric, as illustrated in Figure 7.

Figure 7 – PCI Method Equation [39]

$$PCI = \frac{\sum_{i=1}^{P} CCI_i - \sum_{i=1}^{P} MinCCI_i}{\sum_{i=1}^{P} MaxCCI_i - \sum_{i=1}^{P} MinCCI_i} \times 100$$

Where,

$CCI_i =$ Commonality index of the component $i = n_i \times f_{1i} \times f_{2i} \times f_{3i}$

$MaxCCI_i =$ Maximum possible commonality index for the component $i = N$

$MinCCI_i =$ Maximum possible commonality index for the component

$$i = n_i \times \frac{1}{n_i} \times \frac{1}{n_i} \times \frac{1}{n_i} = \frac{1}{{n_i}^2}$$

$P =$ Total number of non-differentiating components that can potentially be standardized across models

$N =$ Number of products in the family

$n_i =$ Number of family products that have component *i*

$f_{1i} =$ Size and shape factor for the component *i*

$f_{2i} =$ Material and manufacturing process factor for the component *i*

$f_{3i} =$ Fixing and assembly factor for the component *i*

Replacing the CCI_i, $MaxCCI_i$, and $MinCCI_i$ values in the expression shown in Figure 9 gives the following formula for PCI:

$$PCI = \frac{\sum_{i=1}^{P} n_i \times f_{1i} \times f_{2i} \times f_{3i} - \sum_{i=1}^{P} \frac{1}{{n_i}^2}}{(P \times N) - \sum_{i=1}^{P} \frac{1}{{n_i}^2}} \times 100$$

The main advantage of PCI is that the method relies on measurable and quantifiable criteria; applying a simple percentage metric of standard components lies mainly within the researcher's subjectivity. In addition, PCI provides project teams with a method to compare their results with other industry companies (e.g., thermometers), highlighting potential improved design efficiency opportunities.

3. Research Methods

This study aims at developing a modularization protocol for products, using a refrigerator as a case study to evaluate the conceptual model, comparing the results with an actual product developed by a home appliance organization. Thus, the research method is applied-developmental [40]. The case study uses an empirical methodological approach to investigate a contemporary phenomenon in a real context by gathering and analyzing multiple evidence sources [41]. We chose this approach because modularity is an appealing concept within product development decisions. We conducted this case study by following two steps:

- *Data collection procedures*: To obtain information about the chosen product to modularize (refrigerator), we used interviews with engineers and nonparticipant observations within the company. Additionally, we collected secondary data regarding refrigerators, mainly available on the internet (e.g., specialized websites in the home appliance industry). We focused on product architecture features and customer requirements.
- *Modularization protocol development and application*: we carried out procedures to build the modularization protocol based on methods available in the literature; we then developed a combined approach involving the MFD and PCI methods. After gathering data, we applied the protocol to develop the modularized refrigerator and then compare the model's results to a product developed by a multinational company in the home appliance industry. This step faced some limitations since most real case data were very strategic for the company, inhibiting a more in-depth analysis.

3.1. Data collection procedures

We chose a refrigerator manufacturer to develop product modularization methods because it has a product engineering sector within its unit. This feature contributed to a complete understanding of the higher value-added activities in product development, which we analyzed to apply the MFD and PCI methods later. After choosing the home appliance company (we call it Company X due to confidentiality), we asked the product engineering team for documents about a previously developed project to avoid jeopardizing the company's strategies. Nevertheless, we obtained little data regarding the project. The company's confidentiality and compliance policy are considerably rigorous; its employees could not share any data related to previous projects. Thus, we faced limitations in terms of access to data. The only information we could obtain about the actual product was (i) a representation of the modular structure that they use and its subdivisions for comparison with the one we obtained, and (ii) feedback from some experts of the product engineering team regarding our product modularization protocol after applying it to develop a refrigerator as a case study, to verify its compatibility in terms of results and adequacy to a real context.

3.2. Modularization protocol development and application

As presented in the previous section, we investigated the modularization methods available in the literature, exploring their main features, steps, potentials, and limitations. Then, we decided which modularization method to apply. Among the presented methods, we chose MFD due to the application of specific tools that translate consumer requirements for product properties, the presence of evaluation phases, and more straightforward implementation. Additionally, MFD is the only method covering all three main stages (decomposition, integration, and evaluation/assessment) to modularize a product in terms of standardized and robust steps. We then raised conversations with engineers who worked or were working in the field, and research in specialized forums covering customer requirements and the product properties required to meet those requirements. Next, we correlated this information through the first QFD matrix (House of Quality – HoQ). Then, we provided technical solutions for the product properties and correlated them through the DPM matrix.

We modularized the technical solutions obtained through the MIM matrix. We used the twelve modularization guidelines provided by [13] as a theoretical foundation. Furthermore, we grounded our modularity decisions to generate the modular concept through the modularization guidelines established by [16], and then we developed a dendrogram [42] to indicate the modules. Based on the MIM and DPM matrices results, we generated a dendrogram using the Action Stat® software coupled with Excel®. Then, we analyzed the result of this dendrogram, which resulted in the modules. The last step of MFD was to define interfaces between the obtained modules. With the defined modules, we compared our results with the information about the company's modular structure.

Finally, we chose a module that stood out among the matrices to apply the PCI metric and one of its components. We used PCI to analyze the potential to explore commonality in a specific product component. We chose the component based on information available on secondary sources of evidence (e.g., customer desires available on the internet) because the home appliance company that we contacted did not provide such information due to strategic issues. Moreover, we researched the different component models used in different refrigerator families around the world. After obtaining the data, we divided the component into substructures that served as a basis for PCI application. Subsequently, we analyzed and discussed the results, casting light on some alternatives and drawbacks regarding reducing manufacturing costs in the product architecture or evaluating customer acceptance after a whole standardized component among the company's various refrigerator models.

4. Findings

This section presents the results of applying MFD, modularization guidelines, and PCI in the investigated case. Below we outline each step to carry out the selected product modularization approaches.

4.1. Customer Requirements Definition

At this stage, we define customer requirements based on internet surveys and meetings with engineers who were or have been on the refrigerator design development team. The information obtained demonstrates that the primary needs of customers relate to (i) capacity, (ii) size, (iii) price, (iv) energy-saving, (v) type of doors, (vi) facilities, and (vii) design. We assigned a score for each of these requirements, representing the importance of the customer's requirement. First, we defined the main customer requirements and their respective scores for a refrigerator (Table 3). Next, we designed the project scope by translating customer requirements into design requirements (controllable and measurable – Table 4). Once we define the product properties, they are met with customer requirements using the QFD matrix. The criteria used were: 5 for strong ratio, 3 for average/medium ratio, and 1 for weak ratio. When there is no relationship, the score is zero (0), and the cell remains blank. Figure 8 shows the resulting QFD matrix.

Table 3 – Main customer requirements for a refrigerator

Requirements	Score (from 1 to 5)
Low energy consumption	3
Silent	2
Airtight	3
Good food preservation	4
Good storage capacity	5
Easy to open and close	3
Easy to clean	4
Easy to add/remove shelves and drawers	2
Good visibility and access inside the refrigerator	3
Durability	4
Easy installation	3
Spare parts	3
Visually attractive, beautiful design	5
Quick freezing of food	4
Low price	5
Variety (one door, two doors, water dispenser)	3

Table 4 – Product requirements, objectives ad undesirable outputs

Product Requirement	Objective	Undesirable outputs
Modularity	Communalizing as many components as possible to reduce costs and enable a broader range of options	Predominantly integral architecture
Using good materials	Making the refrigerator visually attractive and ensuring quality performance	Increased costs and use of materials with mechanical characteristics above those required
Low manufacturing cost	Maximizing cost savings	High manufacturing cost
Dimensions (height, width, and length)	Designing a product that fits a standard kitchen size	It does not fit in most kitchens
Easy to assemble and disassemble	Ensuring that the product is easy to install, maintain, and customize	Complex assembly product and complicated installation
Operating frequency	Guaranteed service life of more than ten years	The product fails during its life cycle
Total capacity (L)	Maximizing refrigerator space	Low volume efficiency (usable/total)
Easy to manufacture	Enabling faster production	It takes time to produce a unit
Offering a variety of options	Offering a range of products that allow client customization	Customer dissatisfaction
Low energy consumption	Ensuring that the refrigerator falls into the "A" category of consumption established by INMETRO	The product consumes excess electricity
Cooling and freezing/thawing speed	Maximizing customer satisfaction	More than one hour to refrigerate/freeze
Insulation capacity	Minimizing heat exchange with the environment	Refrigerator consumes much energy to replace the absorbed heat
Ensuring user safety	Enabling the best ergonomics for use and covering parts that may cause cuts	Increased product cost
12-month warranty	Ensuring that the customer is not harmed by manufacturing errors	-
Low noise level	Minimizing noise	Noisy product
Complying with laws and regulations	Ensuring that the product meets current legislation	Noncompliance with some regulations

Figure 8 – QFD matrix of the refrigerator

Relationship		
Strong	●	(5)
Medium	○	(3)
Weak	Δ	(1)

	Modularity	Dimensions (height, width and length)	Easy to manufacture	Easy to assemble and disassemble	Low manufacturing cost	Low energy consumption	Isolation capacity	Cooling and freezing/thawing speed	Low noise level	Utilize good materials	Offer variety of options	Total capacity (L)	12 months warranty	Operating frequency	Ensuring user safety	Comply with laws and regulations	Importance for the consumer
Low energy consumption		▽			●	●	●	●	○			▽		●		○	3
Silent						○	●	○	●	○				●	○	○	2
Be airtight		▽	○		●	●	●	○	▽	●					●		3
Preserve food well						●	●	●		○							4
Good storage space	○	●			●						○	●					5
Easy to open and close	▽		▽	○						▽				●	●		3
Easy to clean		○		○				○		▽		●			○		4
Easy to add/remove shelves and drawers	●	○		●							●				○		2
Good visibility and access inside the refrigerator		●		▽							○	●					3
Durability	○		○		●	▽				●			●	●		○	4
Easy installation	○	○		●							▽				○		3
Have spare parts	●			●						○			○	▽			3
Visually attractive, beautiful design	●	○	○		●					●	●	○					5
Freezes food quickly		▽				●	●	●			▽	○		○			4
Low price	●	●	●	○	●	▽			▽	●	○	○	●	○			5
Must have variety (1 door, 2 doors, water dispenser)	●	▽	●	▽					▽	▽	●	○					3
Total Scoring	129	120	79	82	125	85	80	82	30	122	96	114	54	90	63	27	
Priority	1º	4º	12º	9º	2º	8º	11º	9º	15º	3º	6º	5º	14º	7º	13º	16º	

4.2. Selection of technical solutions

The product's properties must be solved to be inserted in the product in a way that meets its needs and expectations. There is no specific method for defining technical solutions. [13] argued that there is usually more than a single proper solution. However, all solutions must be described and documented, and the decomposition of the product must not reach the level of screws, nuts, and washers.

There are two ways for the functional analysis to define technical solutions [43]: top-down or bottom-up. The top-down analysis describes the product's primary function, which is deployed at the other levels until reaching the functions to be achieved. From this, the technical solutions for these functions are defined. In the bottom-up analysis, the starting point is an existing product, questioning all technical solutions. Also, new solutions might emerge.

We decided to adopt the bottom-up analysis since the starting point is an existing product, questioning its technical solutions and providing new solutions. Thus, based on exploded views and 2D drawings of the refrigerators, we offered 30 technical solutions (Table 5). The properties of the products must be compared with the technical solutions using DPM. The criteria used are the same as those of QFD (0, 1, 3, and 5). Inadequate filling may suggest modules strongly influenced by the engineering view, with a narrow strategy [44]. Figure 9 shows the obtained DPM.

Table 5 – Technical solutions developed

Technical Solutions		
Lower hinge	Ice mold	Bivolt
Intermediate hinge	Top cabinet	Can holders
Top hinge	Bottom cabinet	Freezer shelves
Adjustable foot	Bottom door	Condenser
Digital thermostat	Top door	Evaporator
Led lamp	Vegetable drawer	Rotary compressor
Light switch	Door shelf	Fluid R134A
Tempered glass shelf	Lower door handle	Safety valve
Door rubber	Top door handle	Egg holder
Dispensing with ice water	Frost free	Insulating

4.3. Generation of the modular concept

The next step is to generate the Module Indication Matrix (MIM – Figure 10), which correlates technical solutions with modularization guidelines. Twelve strategic points justify the formation of the modules. MIM and DPM are analyzed together to indicate which technical solutions are most similar, which are then clustered in the same module. We simulated the indication of the best clusters using hierarchical clustering statistical software. The software's answer is a dendrogram (Figure 11). However, it is essential to point out that dendrograms are rarely used *ipsis litteris*. Therefore, they do not offer exact solutions; hierarchical clusters must be interpreted and analyzed to decide which ones should be modules or not [44]. Very disparate results may indicate that the DPM and MIM score is not adequate and should be reviewed. As a result, eight different modules were obtained (Table 6).

Figure 9 – DPM developed

Relationship		
Strong	●	(5)
Medium	○	(3)
Weak	▽	(1)

Technical Solutions	Modularity	Dimensions (height, width and length)	Easy to manufacture	Easy to assemble and disassemble	Low manufacturing cost	Low energy consumption	Isolation capacity	Cooling and freezing/thawing speed	Low noise level	Utilize good materials	Offer variety of options	Total capacity (L)	12 months warranty	Operating frequency	Ensuring user safety	Comply with laws and regulations	Scoring
	Product Properties																
Lower hinge	●	○	●	●					▽	●	○			●	▽		3251
Intermediate hinge	●	○	●	●					▽	●	○			●	▽		3251
Top hinge	●	○	●	●					▽	●	○			●	▽		3251
Adjustable foot	●	○	○	●	○					▽	●				○		2818
Digital thermostat	▽				●	○		▽		○	●						1937
Led lamp					○	○				○	○						1284
Light switch						▽								○			355
Cabinet shelves	▽		○		●					●	●				○		2270
Ice mold	●		▽	▽	○						●	▽					1775
Top cabinet	●	●	●	○	○		○	○		○		●					3683
Bottom cabinet	○	●	●	○	○		○	○		○	○	●					3713
Bottom door	▽	○															489
Top door	○	○									○						1035
Vegetable drawer	●		▽	▽	○						●	▽					1775
Door shelf	●		▽	○	▽					▽	●	●					2267
Lower door handle	●	▽	▽	○	▽					▽	▽			○	▽		1766
Top door handle	●	▽	▽	○	▽					▽	▽			○	▽		1766
Frost free	○				●			●			●			▽			1992
Dispensing with ice water	●			▽	●			○			●	▽		▽			2282
Egg holder	●		▽	▽	○						●	▽					1775
Can holders	●		▽	▽	○						●	▽					1775
Freezer shelves	▽	▽	●	○	●			▽	▽		▽	○			▽		2128
Door rubber		○		○			●		○	○						▽	1489
Insulating		○	●		○		●	●	●	○							2456
Condenser					●	○		●								▽	1317
Evaporator					●	○		●								▽	1317
Rotary compressor					○	●		●	●					○		▽	1657
Fluid R134A						○	○	●							▽	●	1103
Safety valve													○		●	●	612
Bivolt											●		▽		○		723
QFD Result	129	120	79	82	125	85	80	82	30	122	96	114	54	90	63	27	

Figure 10 – MIM developed

Relationship		
Strong	●	(5)
Medium	○	(3)
Weak	Δ	(1)

Modularization guidelines		Lower hinge	Intermediate hinge	Top hinge	Adjustable foot	Digital thermostat	Led lamp	Light switch	Cabinet shelves	Ice mold	Top cabinet	Bottom cabinet	Bottom door	Top door	Vegetable drawer	Door shelf
Product development	Carry-over	●	●	●	●	○	●	●	●	●	●	●	●	●	●	●
	Technological Evolution	▽	▽	▽	○	○				○	▽	▽			○	
	Design Changes Planning															
Variety	Technical specification	▽	▽	▽	▽				▽	○	○	○	○	○	○	▽
	Style				▽	○			●	●	●	●	●	●	●	●
Manufacturing	Common Unity	●	●	●	○	○			●	○	●	●	●	●	○	●
	Process and Organization	●	●	●	○	○			○	●			●	●	●	○
Quality	Separate Tests	●	●	●	○		●		○	●			▽	▽	●	○
Purchase	Ready-made products purchase	●	●	●	○		●	●	○	●					●	○
After-market	Maintenance and maintainability	●	●	●	▽		●	●	●		▽	▽	●	●		●
	Update	○	○	○									○	○		
	Recycling	●	●	●					●	●	▽	▽			●	●
	∑ TOTAL	40	40	40	23	15	20	15	35	39	21	21	32	32	39	35
	Ranking	1º	1º	1º	10º	16º	15º	16º	7º	2º	13º	13º	6º	6º	2º	4º

Modularization guidelines		Lower door handle	Top door handle	Frost free	Dispensing with ice water	Egg holder	Can holders	Freezer shelves	Door rubber	Insulating	Condenser	Evaporator	Rotary compressor	Fluid R134A	Safety valve	Bivolt
Product development	Carry-over	●	●	●	○	●	●	●	●	●	●	●	●	●	●	●
	Technological Evolution	▽	▽	●	○	○	○			▽	▽	▽	▽	▽	▽	
	Design Changes Planning										○	○	○	○	○	
Variety	Technical specification	●	●	▽	●	○	○	▽								○
	Style	●	●		▽	●	●	●	▽							
Manufacturing	Common Unity	●	●	○		○	○	●	●	●	●	●	●	●	●	○
	Process and Organization	●	●		●	●	●	○	●	○						
Quality	Separate Tests	○	○			●	●	○	○	○	●	●	●	●	●	
Purchase	Ready-made products purchase	●	●			●	●	○	●	●	●	●	●	●	●	
After-market	Maintenance and maintainability	●	●					●	●		●	●	●	●	●	○
	Update			●	●											
	Recycling					●	●	●	●							
	∑ TOTAL	39	39	19	22	39	39	35	34	22	29	29	29	29	29	14
	Ranking	2º	2º	14º	11º	2º	2º	6º	5º	11º	9º	9º	9º	9º	9º	17º

Figure 11 – Software-generated dendrogram

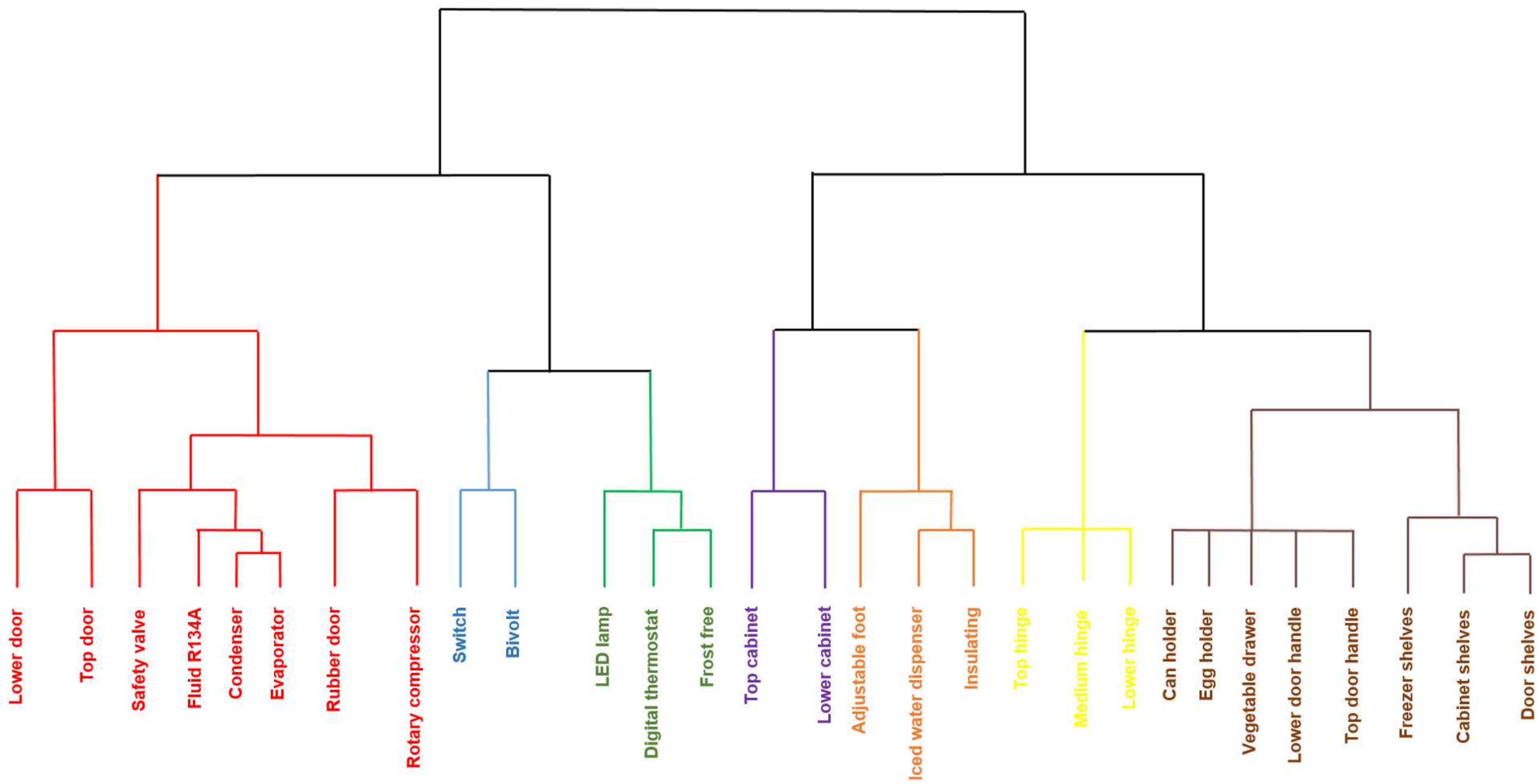


Table 6 – Modules obtained through MFD application

Modularization obtained		
Module number	**Module name**	**Components**
Module 1	Hinges	Top hinge
		Lower hinge
		Medium hinge
Module 2	Facilities	Ice mold
		Can holder
		Egg holder
		Vegetable drawer
Module 3	Doors	Lower door
		Top door
		Door rubber
		Insulating
		Top door handle
		Lower door handle
Module 4	Shelves	Door shelf
		Main cabinet shelf
		Freezer shelf
Module 5	Cooling system	Compressor
		Evaporator
		Condenser
		Fluid R134A
		Frost free
		Safety valve
Module 6	Cabinet	Lower cabinet
		Top cabinet
		Adjustable foot
		Insulating
Module 7	Water dispenser	Water dispenser
Module 8	Electronic / Electrical part	Digital thermostat
		LED lamp
		Bivolt
		Switch

4.4. Analysis of the modular concept

The next stage of the MFD method analyzes the concepts generated for their interfaces through the IM. This matrix correlates a module with all others based on its interface conditions. For this, we used [13]'s classification. Figure 12 shows the obtained IM, together with the eight modules obtained previously. With the IM ready, we built the product management map (PMM). This map has the 3 MFD matrices (QFD, DPM, and MIM) plus the IM. The PMM shows a broad view of the entire development and which customer requirements, product ownership, and strategies influence the grouping of technical solutions into modules. It also shows the path taken during the modularization process. Figure 13 shows the PMM.

Figure 12 – Interface matrix developed

Modularization obtained		
Module number	**Module name**	**Components**
Module 1	Hinges	Top hinge
		Lower hinge
		Medium hinge
Module 2	Facilities	Ice mold
		Can holder
		Egg holder
		Vegetable drawer
Module 3	Doors	Lower door
		Top door
		Door rubber
		Insulating
		Top door handle
		Lower door handle
Module 4	Shelves	Door shelf
		Main cabinet shelf
		Freezer shelf
Module 5	Cooling system	Compressor
		Evaporator
		Condenser
		Fluid R134A
		Frost free
		Safety valve
Module 6	Cabinet	Lower cabinet
		Top cabinet
		Adjustable foot
		Insulating
Module 7	Water dispenser	Water dispenser
Module 8	Electronic / Electrical part	Digital thermostat
		LED lamp
		Bivolt
		Switch

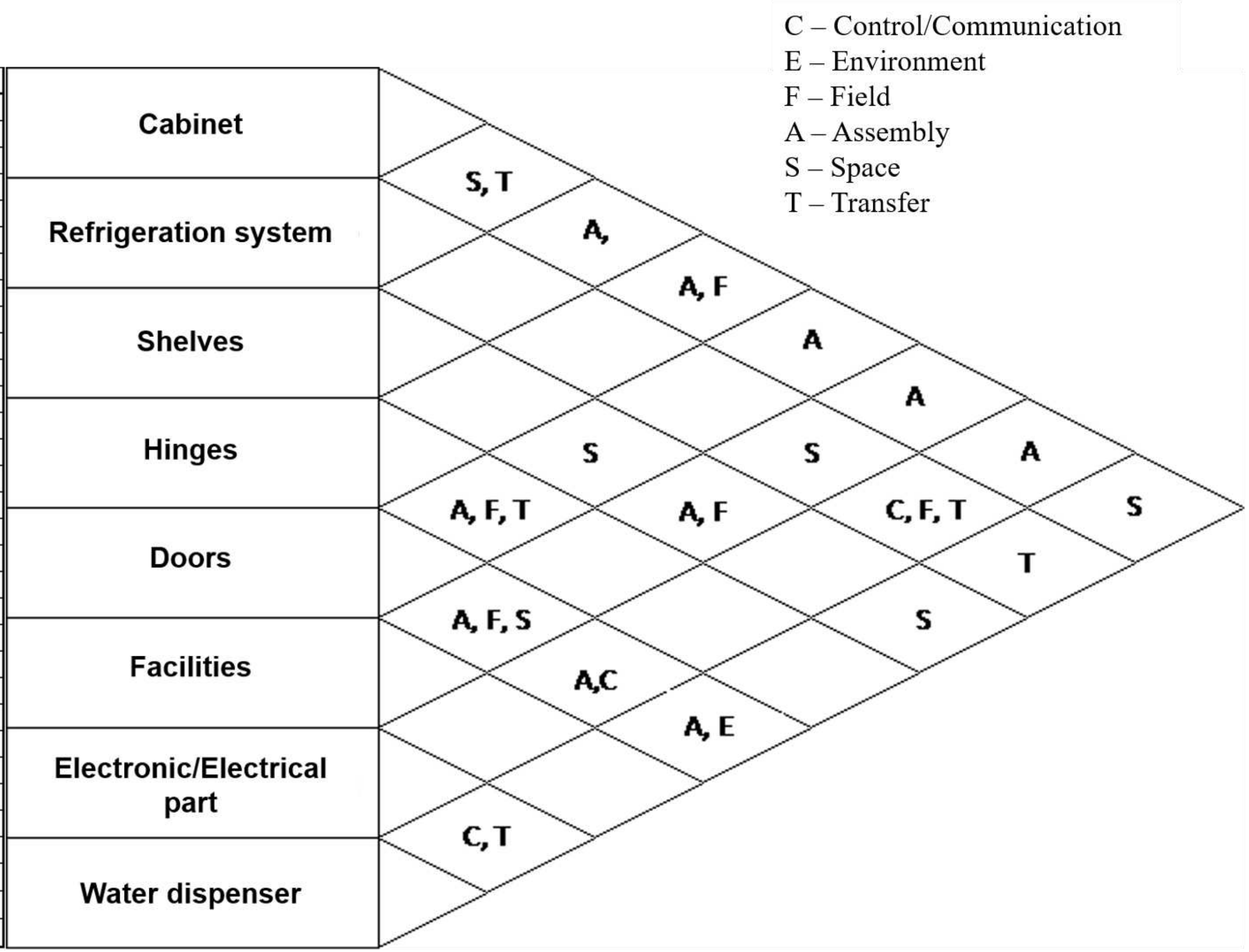
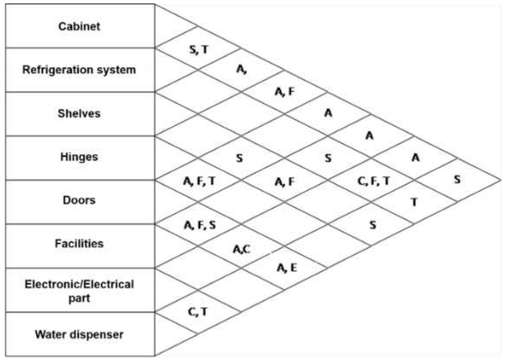


Figure 13 – PMM developed

Customer requirements \ Product requirements	Modularity	Dimensions (height, width and length)	Easy to manufacture	Easy to assemble and disassemble	Low manufacturing cost	Low energy consumption	Isolation capacity	Cooling and freezing/thawing speed	Low noise level	Utilize good materials	Offer variety of options	Total capacity (L)	12 months warranty	Operating frequency	Ensuring user safety	Comply with laws and regulations	Importance for the consumer
Low energy consumption		▽			●	●	●	●	○			▽		●		○	3
Silent						○	●	○	●	○				●	○	○	2
Be airtight		▽	○		●	●	●	○	▽	●					●		3
Preserve food well						●	●	●		○							4
Good storage space	○	●			●						○	●					5
Easy to open and close	▽		▽	○						▽				●	●		3
Easy to clean		○		○				○		▽		●			○		4
Easy to add/remove shelves and drawers	●	○		●							●				○		2
Good visibility and access inside the refrigerator		●		▽							○	●					3
Durability	○		○		●	▽				●			●	●		○	4
Easy installation	○	○		●							▽				○		3
Have spare parts	●			●						○			○	▽			3
Visually attractive, beautiful design	●	○	○		●					●	●	○					5
Freezes food quickly		▽				●	●	●			▽	○		○			4
Low price	●	●	●	○	●	▽			▽	●	○	○	●	○			5
Must have variety (1 door, 2 doors, water dispenser)	●	▽	●	▽					▽	▽	●	○					3
Total scoring	129	120	79	82	125	85	80	82	30	122	96	114	54	90	63	27	
Prioritization	1°	4°	12°	9°	2°	8°	11°	9°	15°	3°	6°	5°	14°	7°	13°	16°	

Relationship		
Strong	●	(5)
Medium	○	(3)
Weak	Δ	(1)

C – Control/Communication
E – Environment
F – Field
A – Assembly
S – Space
T – Transfer



Technical Solutions × Product requirements

Technical Solutions	Modularity	Dimensions (height, width and length)	Easy to manufacture	Easy to assemble and disassemble	Low manufacturing cost	Low energy consumption	Isolation capacity	Cooling and freezing/thawing speed	Low noise level	Utilize good materials	Offer variety of options	Total capacity (L)	12 months warranty	Operating frequency	Ensuring user safety	Comply with laws and regulations	Total
Lower hinge	●	○	●	●					▽	●	○			●	▽		3251
Intermediate hinge	●	○	●	●					▽	●	○			●	▽		3251
Top hinge	●	○	●	●					▽	●	○			●	▽		3251
Adjustable foot	●	○	○	●	○					▽	●				○		2818
Digital thermostat	▽				●	○		▽		○	●						1937
Led lamp					○	○				○	○						1284
Light switch						▽								○			355
Cabinet shelves	▽		○		●					●	●				○		2270
Ice mold	●		▽	▽	○						●	▽					1775
Top cabinet	●	●	●	○	○		○	○		○		●					3683
Bottom cabinet	○	●	●	○	○		○	○		○	○	●					3713
Bottom door	▽	○															489
Top door	○	○									○						1035
Vegetable drawer	●		▽	▽	○						●	▽					1775
Door shelf	●		▽	○	▽					▽	●	●					2267
Lower door handle	●	▽	▽	○	▽					▽	▽			○	▽		1766
Top door handle	●	▽	▽	○	▽					▽	▽			○	▽		1766
Frost free	○				●			●			●			▽			1992
Dispensing with ice water	●			▽	●			○			●	▽		▽			2282
Egg holder	●		▽	▽	○						●	▽					1775
Can holders	●		▽	▽	○						●	▽					1775
Freezer shelves	▽	▽	●	○	●			▽	▽		▽	○			▽		2128
Door rubber		○		○			●		○	○						▽	1489
Insulating		○	●		○		●	●	●	○							2456
Condenser					●	○		●								▽	1317
Evaporator					●	○		●								▽	1317
Rotary compressor					○	●		●	●					○		▽	1657
Fluid R134A						○	○	●							▽	●	1103
Safety valve													○		●	●	612
Bivolt											●		▽		○		723

Modularization guidelines

Technical Solutions	Product development: Carry-over	Product development: Technological Evolution	Product development: Design Changes Planning	Variety: Technical specification	Variety: Style	Manufacturing: Common Unity	Manufacturing: Process and Organization	Quality: Separate Tests	Purchase: Ready-made products purchase	After-market: Maintenance and maintainability	After-market: Update	After-market: Recycling	Σ TOTAL	Ranking
Lower hinge	●	▽		▽		●	●	●	●	●	○	●	40	1º
Intermediate hinge	●	▽		▽		●	●	●	●	●	○	●	40	1º
Top hinge	●	▽		▽		●	●	●	●	●	○	●	40	1º
Adjustable foot	●	○		▽	▽	○	○	○	○	▽			23	10º
Digital thermostat	○	○			○	○	○						15	16º
Led lamp	●							●	●	●			20	15º
Light switch	●								●	●			15	16º
Cabinet shelves	●			▽	●	●	○	○	○	●		●	35	7º
Ice mold	●	○		○	●	○	●	●	●			●	39	2º
Top cabinet	●	▽		○	●	●				▽		▽	21	13º
Bottom cabinet	●	▽		○	●	●				▽		▽	21	13º
Bottom door	●			○	●	●	●	▽		●	○		32	6º
Top door	●			○	●	●	●	▽		●	○		32	6º
Vegetable drawer	●	○		○	●	○	●	●	●			●	39	2º
Door shelf	●			▽	●	●	○	○	○	●		●	35	4º
Lower door handle	●	▽		●	●	●	●	○	●	●			39	2º
Top door handle	●	▽		●	●	●	●	○	●	●			39	2º
Frost free	●	●		▽		○					●		19	14º
Dispensing with ice water	○	○		●	▽		●				●		22	11º
Egg holder	●	○		○	●	○	●	●	●			●	39	2º
Can holders	●	○		○	●	○	●	●	●			●	39	2º
Freezer shelves	●			▽	●	●	○	○	○	●		●	35	6º
Door rubber	●				▽	●	●	○	●	●		●	34	5º
Insulating	●	▽				●	○	○	●				22	11º
Condenser	●	▽	○			●		●	●	●			29	9º
Evaporator	●	▽	○			●		●	●	●			29	9º
Rotary compressor	●	▽	○			●		●	●	●			29	9º
Fluid R134A	●	▽	○			●		●	●	●			29	9º
Safety valve	●	▽	○			●		●	●	●			29	9º
Bivolt	●			○		○				○			14	17º

Modularization obtained

Module number	Module name	Components
Module 1	Hinges	Top hinge
		Lower hinge
		Medium hinge
Module 2	Facilities	Ice mold
		Can holder
		Egg holder
		Vegetable drawer
Module 3	Doors	Lower door
		Top door
		Door rubber
		Insulating
		Top door handle
		Lower door handle
Module 4	Shelves	Door shelf
		Main cabinet shelf
		Freezer shelf
Module 5	Cooling system	Compressor
		Evaporator
		Condenser
		Fluid R134A
		Frost free
		Safety valve
Module 6	Cabinet	Lower cabinet
		Top cabinet
		Adjustable foot
		Insulating
Module 7	Water dispenser	Water dispenser
Module 8	Electronic / Electrical part	Digital thermostat
		LED lamp
		Bivolt
		Switch

4.5. Enhancing the modules

The last step of the MFD method consolidates all modularization stages, specifying modules and interfaces, customer needs, technical solutions, and modularity strategies [13]. This phase also supports project detailing and the modular concept's implementation planning. All information must be described in a standardized format and disseminated to the areas involved in the project. Figure 14 shows a developed model for this document.

Figure 14 – A standard suggestion for specifying the modules [38]

Accountable:	**Module's name** **Suggestive name with easy product link** **Add the module image**
Objective/Goal:	**List the strategies that must be met** **MIM Information**
Technical Solutions:	**List the technical solutions that make up the product** **PMM information or dendrogram**
Interfaces with:	**List the modules that have an interface and the type of interface** **IM Information**
Consider:	**List customer requirements that have been affected** **QFD information**

Similar to what [38] developed, the present work aims to apply modularization principles in product architecture development. The fifth phase of the MFD method generates information to design the modules' components and interfaces based on the modular concept.

4.6. Comparing the obtained modularization in the protocol with the existing product modularization

One of the objectives of this paper is to compare the existing modularization with the one used by Company X through the MFD method. Figure 15 shows the comparison. The result obtained through the modularization process is less complex than the existing one. It indicates that the company already has integrated modularity within its project sector.

Figure 15 – Modularization developed x Existing modularization in Company X

Modularization obtained		
Module number	**Module name**	**Components**
Module 1	Hinges	Top hinge
		Lower hinge
		Medium hinge
Module 2	Facilities	Ice mold
		Can holder
		Egg holder
		Vegetable drawer
Module 3	Doors	Lower door
		Top door
		Door rubber
		Insulating
		Top door handle
		Lower door handle
Module 4	Shelves	Door shelf
		Main cabinet shelf
		Freezer shelf
Module 5	Cooling system	Compressor
		Evaporator
		Condenser
		Fluid R134A
		Frost free
		Safety valve
Module 6	Cabinet	Lower cabinet
		Top cabinet
		Adjustable foot
		Insulating
Module 7	Water dispenser	Water dispenser
Module 8	Electronic / Electrical part	Digital thermostat
		LED lamp
		Bivolt
		Switch

Existing modularization (Company X)		
Module number	**Module name**	**Components**
Module 1	Chassis	Chassis structure
		Internal coating
		Isolation
		Base
		Feet and wheels
Module 2	Doors	Door structure
		Internal coating
		Isolation
		Puller
Module 3	Packing	External packing
		Inner packing
Module 4	Accessories	Fasteners (screws, nuts and washers)
		Tapes
		Instruction manual
Module 5	Electric/Electronic	First user interface
		Second user interface
		Power plate
		Wiring and protection
		Power cable
		Sensors
		Heaters
		Artificial intelligence
		Lighting
Module 6	Interiors	Shelves
		Drawers
		Door shelves
		Functional compartments
Module 7	Air flow	Air ducts
		Air treatment
		Fans, air controllers
Module 8	Cooling system	High pressure system
		Compressors
		Low pressure system
		Defrost system
Module 9	Ice and water	Water treatment
		Ice dispenser
		Water dispenser

4.7. Product Line Commonality Index (PCI) application

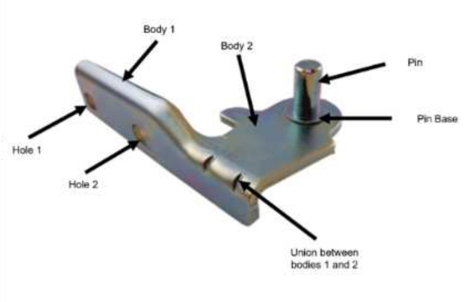
Analyzing MIM and DPM's results proportionately, the modules that scored the most were hinges, cabinets, and facilities. Due to the complexity of design, composition, the number of components, and overall function within these three, we chose the hinge module to apply the PCI. This module consists of three components: upper hinge, intermediate hinge, and lower hinge. They all have the same global function: to make it possible to open and close the doors, in addition to serving as a support so that the doors do not fall.

Among the three different types mentioned, we chose the intermediate hinge to continue the work. By researching the different hinge models the company works with, we found that intermediate hinges have little variety. Upper and lower hinges are used in several refrigerators (industrial refrigerators, minifridges, single-door refrigerators, side-by-side refrigerators). Therefore, they have the most diverse shapes and sizes, making it challenging to apply PCI. Thus, our method consisted of splitting the hinges into seven substructures and comparing these substructures with the different models raised during the research. The result shows the percentage of shared structure between the models, giving the engineering team an idea of the work needed to ensure that the structure is shared across 100% of the models.

Due to the company's compliance and confidentiality policies, it was unfeasible to obtain more detailed information about components or numbers concerning how many intermediate hinges exist in the different models across the world. Therefore, we searched the internet towards virtual stores specialized in refrigerators components. We found that normally, refrigerators use seven different intermediate hinges; however, they are remarkably similar and perform the same functions. Thus, the module has a significant potential for commonality application. Once we defined the parameters, we applied the PCI method (Figure 16).

Figure 16 – Division of an intermediate hinge into seven substructures

Substructures	n_i	$MinCCI_i$	f_{1i}	f_{2i}	f_{3i}	CCI_i
Hole 1	7	0.0204	0.57	0.71	1.00	2.86
Hole 2	7	0.0204	0.57	0.71	1.00	2.86
Pin	7	0.0204	0.57	0.86	1.00	5.14
Pin Base	7	0.0204	0.57	0.71	1.00	3.57
Body 1	7	0.0204	0.57	1.00	1.00	6.00
Body 2	7	0.0204	0.57	1.00	1.00	4.00
Union between bodies 1 and 2	7	0.0204	0.57	0.57	1.00	2.29



$\sum MinCCI_i$	0.1429
P	7
N	7
$\sum CCI_i$	26.71
PCI	54.39%

5. Discussion and managerial implications

The modularization of an existing product by evaluating customer requirements and product properties was developed based on publicly available materials and interviews with customers and experts. The first matrix in MFD proved to be valuable for identifying customers' requirements. We also obtained technical solutions using the bottom-up process from exploded views and component lists, generating 30 technical solutions. Subsequently, we obtained a dendrogram, which presented expressive clusters within the product architecture, as pointed out by [13,37,42]. However, we could not use them directly; therefore, we conducted data analysis and further adjustments to build the product modules.

Comparing the two modular structures obtained, we observed that the modularization strategy has indications of being considerably well-structured within Company X. The comparison also indicates that the solutions of the MFD method are more generic than the solutions developed for Company X's refrigerator. For instance, the company could build the airflow system into the cooling system. However, in the modular system used by the company, there is a unique and separate airflow module. Nonetheless, the generic results were expected, as MFD is a versatile tool for many companies because of its general modularization guidelines [26]. We also observed during the comparison that the leading company's modules are composed mainly of subsystems; when applying the MFD, the technical solutions generated were predominantly components. Company X uses two submodules in the "Cooling System" module, a high-pressure system and a low-pressure system.

Our study identified components that would be technical solutions of a refrigerator and grouped them into a module that bears the company's exact module name. Albeit the differences between the systems, the comparison shows that the MFD method may be a relevant starting point for modularizing a product and may bring significant solutions for companies interested in modularizing their products and services. Evidence indicates that the product architecture obtained through the modularization protocol does not contradict the existing product, having few substantial differences. We observed that in the adopted modular system, the hinge part is absent. Thus, we suggest integrating it into the door or chassis module due to its interface with such components.

Moreover, to measure the diversity of hinges performing the same function and that theoretically could be equal, we searched for the company's intermediate hinges and found seven different models. According to the PCI method, there is only a 54.39% level of commonality between those hinges. Considering that intermediate hinges perform the same function, we suggest that the company may be wasting resources by manufacturing different components. The result obtained through PCI could be considered for future product development in terms of costs and quality.

However, we also emphasize that it is necessary to consider whether changing the intermediate hinges (i.e., greater standardization) would negatively impact the market acceptance of the current products. For example, in some cases, an excessive commonality level might create issues in product variety because products become remarkably similar, with higher degrees of common parts among various products and brands [45]. Furthermore, conducting a solution focused solely on costs can have reverse effects if an analysis of customer requirements is not well-accomplished. Thus, both scholars and practitioners must be careful when giving recommendations regarding product architecture changes.

6. Conclusions

Our study presents the development and application of a new modularization protocol mainly based on the MFD method and PCI metric. Our main contribution in this study is to analyze some of the product modularization methods available in the literature and the development of a modularization approach to new products or product updates. The protocol and further analysis could be applied to other types of products since they follow generic procedures and guidelines that are commonly integrated into companies' product development processes. Another contribution of this paper is the application of the modularization protocol itself. The results obtained through this process showed that modularity might indicate real solutions to develop products. Thus, both MFD and PCI methods can serve as relevant approaches for managers and practitioners when generating new product concepts.

The main limitation in this study is the lack of data provided by Company X because of its strict data confidentiality rules. We gathered most data through some potential customers, experts, and information on refrigerators publicly available on the internet. For further research, we suggest adopting the methods applied in this paper to other higher value-added products and applying the PCI specifically to other components of home appliance companies.

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Availability of data and material (data transparency)

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Code availability

Not applicable.

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Authors' contributions

Not applicable.

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