A modular product design framework for the home appliance industry

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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 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 [6–8]. 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] 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 organize themselves to develop modular products with increased quality and reduced costs and, at the same time, ensure 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 and 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 the quality and environmental requirements. Next, Sect. 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, Sect. 5 discusses the findings of the study. Lastly, Sect. 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.

Modularization methods have some similarities. Therefore, we must analyze those methods by following some criteria to select the most appropriate one then. [33] presents 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

| 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 |
(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 Fig. 1: (i) defining customer requirements, (ii) selecting technical solutions, (iii) generating concepts, (iv) analyzing concepts, and (v) enhancing each module.

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 as follows: (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.

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 Fig. 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 as follows: (i) analyzing product functions; (ii) suggesting technical solutions to fulfill functions; and (iii) connecting technical solutions with product properties at DPM [14].

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 put together for merging and integration” [37, p. 252]. Thus, the objectives of the third step of the MFD method are as follows: 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 – Fig. 4); and outlining the modular concept [14].

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 stan-
dardized 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 – Fig. 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.

**Step 5–Improving modules:** we list all the relevant infor-
mation to define the modules, such as customer require-
ments, 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 as follows:
(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 mar-
et market requirements, (ii) understanding short- and
long-term business strategy of existing projects, and (iii) future
development plans. Furthermore, the project team and func-
tional 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

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**Fig. 2** Simplified QFD matrix (adapted from [11])

| Como? | Modularity | Propriedades do Produto | Peso do consumidor |
|-------|------------|-------------------------|--------------------|
| O quê? |            |                         |                    |
| Requisitos do Consumidor | ● | ● | ● | ○ | 5 |
|                  | ● | ● | ● |      | 3 |
|                  | ○ | ▽ |      |      | 2 |
|                  | ● | ● |      |      | 1 |
| TOTAL |           |                         |                    |
| Prioridade | 5 | 3 | 2 | 1 | 4 |

● Relação forte (5) ○ Relação média (3) ▽ Relação fraca (1)

**Fig. 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 (3) ▽ Weak relationship (1)
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 Fig. 7.

Replacing the $CCI_i$, $MaxCCI_i$, and $MinCCI_i$ values in the expression shown in Fig. 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.

### Table 2: Modularization guidelines [16]

| Product development | Variety | Manufacturing | Quality | Purchase | Aftermarket |
|---------------------|---------|---------------|---------|----------|-------------|
| Carry-over A function can be a separate module where the current technological solution can be taken to a new generation/family of machines | Technical specification Changes can be concentrated to achieve variants in a module | Common unity A function can be separated into a module if it has the same physical solution in all variants | Separate tests A function can be separated into a module when this function can be tested separately | Purchase of ready-made products The function can be treated as a black box because of reduced logistical costs | Maintenance and maintainability Maintenance and repairs can be made easier if a function looks good in a separate module |
| Technological evolution A function can be a single module if it has a technology that is overcome during product life cycle | Style A function can be a separate module if influenced by trends and fashions so that the shapes or colors must be changed | 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 | Updating | Updating |
| Planning for design changes A function can be a separate module if it has characteristics that will be changed according to a plan | | | | Recycling It can be advantageous for concentrating polluting or recyclable materials in the same module or in separate modules | |

### 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

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**Fig. 4 MIM matrix [16]**

| Modulization guidelines | Product development | Variety | Manufacturing | Quality | Purchase | After-market |
|-------------------------|---------------------|---------|---------------|---------|----------|-------------|
|                         | Carry-over          | Technical specification | Common Unity | Separate Tests | Ready-made products purchase | Maintenance and maintainability |
|                         | Technological Evolution |                     | Process and Organization |          |          | Update       |
|                         | Design Changes Planning |               | Style |          |          | Recycling    |
| **Weak relationship (1)** | o                  |         |               |          |          |             |
| **Medium relationship (5)** | o                  |         |               |          |          |             |
| **Strong relationship (5)** | ●                  |         |               |          |          |             |

**Possible modules**

| Function 1 | Function 2 | Function 3 | Function 4 | Function 5 |
|------------|------------|------------|------------|------------|
| 3 12       | 5 3        | 1 18       | 2 14       | 5 1        |

**Scoring**

- 3
- 5
- 1
- 2
- 4
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 two 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. One of the experts is the engineer responsible for the modularization project within the company, while the other is the manager of the global product architecture department.

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

\[
P_{\text{CI}} = \frac{\sum_{i=1}^{P} CCI_i - \sum_{i=1}^{P} \text{Min} CCI_i}{\sum_{i=1}^{P} \text{Max} CCI_i - \sum_{i=1}^{P} \text{Min} CCI_i} \times 100
\]

Where,

\[CC_{\text{II}_{i}} = \text{Commonality index of the component} \quad i = n_i \times f_{II} \times f_{III} \times f_{IV}
\]

\[\text{Max} CCI_i = \text{Maximum possible commonality index for the component} \quad i = N
\]

\[\text{Min} CCI_i = \text{Minimum possible commonality index for the component} \quad i = N
\]

\[n_i = \frac{1}{n_i} \times \frac{1}{n_i} \times \frac{1}{n_i} = \frac{1}{n_i^2}
\]

\[P = \text{Total number of non-differentiating components that can potentially be standardized across models}
\]

\[N = \text{Number of products in the family}
\]

\[n_i = \text{Number of family products that have component } i
\]

\[f_{II} = \text{Size and shape factor for the component } i
\]

\[f_{III} = \text{Material and manufacturing process factor for the component } i
\]

\[f_{IV} = \text{Fixing and assembly factor for the component } i
\]
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.
4.2 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 all technical 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.

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

Table 5 Technical solutions developed

Fig. 8 QFD matrix of the refrigerator
4.3 Generation of the modular concept

The next step is to generate the Module Indication Matrix (MIM – Fig. 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 (Fig. 11). However, it is essential to point out that dendrograms are rarely used ipse 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).

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] 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.

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.

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. We conducted this comparison through data provided by Company X, as well as by consulting two experts from the company. 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.
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 that 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 refrigerator 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 (Fig. 16).

### 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

| 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      | Winter dispenser | Water dispenser |
|                         | Module 8      | Electronic/electrical part | Digital thermostat |

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. Developing a more communized component can generate resources’ savings, bringing economic benefits by reducing operational and development costs, and environmental benefits by reducing resources to manufacture the components. Thus, commonality contributes to modularity’s environmental benefits by simplifying the product design through standardized components [10].

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. It is also important to analyze the manufacturing process changes demanded to enhance product commonality and standardization; otherwise, the product design process will become divorced from the production activities, leading to poor product manufacturability, assembly, and maintainability [46]. Thus, both scholars and practitioners must be careful when giving recommendations regarding product architecture changes.
| Module number | Module name            | Components                  |
|---------------|------------------------|----------------------------|
| Module 1      | Hinges                 | Top hinge, Lower hinge      |
|               |                        | Medium hinge, Ice mold      |
|               |                        | Can holder, Egg holder      |
|               |                        | Vegetable drawer           |
| Module 2      | Facilities             | Lower door, Top door        |
|               |                        | Door rubber, Insulating     |
|               |                        | Top door handle, Lower door handle |
| Module 3      | Doors                  | Door shelf, Main cabinet shelf |
|               |                        | Freezer shelf, Compressor  |
|               |                        | Condenser, Fluid R134A      |
|               |                        | Frost free, Safety valve    |
| Module 4      | Shelves                | Lower cabinet, Top cabinet  |
|               |                        | Adjustable foot, Insulating |
| Module 5      | Cooling system         | Water dispenser, Digital thermostat |
|               |                        | LED lamp, Bivolt, Switch    |
| Module 6      | Cabinet                | Water dispenser             |
|               |                        |                                |
| Module 7      | Water dispenser         |                                |
| Module 8      | Electronic / Electrical part | LED lamp, Bivolt, Switch    |

**Fig. 15**  Modularization developed × modularized refrigerator in Company X

| Module number | Module name  | Components                  |
|---------------|--------------|----------------------------|
| Module 1      | Chassis      | Internal coating            |
|               |              | Isolation, Base             |
| Module 2      | Doors        | Internal coating            |
|               |              | Isolation, Door structure   |
| Module 3      | Packing      | External packing            |
|               |              | Inner packing               |
| Module 4      | Accessories  | Fasteners (screws, nuts and washers) |
|               |              | Tapes                       |
| Module 5      | Electric/Electronic | Wiring and protection |
|               |              | Power cable, Sensors, Heaters|
|               |              | Artificial intelligence, Lighting|
| Module 6      | Interiors    | Drawers, Door shelves       |
|               |              | Functional compartments, Air ducts |
| Module 7      | Air flow     | Air treatment, Fans, air controllers |
| Module 8      | Cooling system | Compressors, Low pressure system |
|               |              | High pressure system, Defrost system |
| Module 9      | Ice and water | Ice dispenser, Water treatment |

**Fig. 16**  Division of an intermediate hinge into seven substructures

| Substructures | \( n_i \) | \( \text{Min}_i \text{CCI}_i \) | \( f_{1i} \) | \( f_{2i} \) | \( f_{3i} \) | \( CCI_i \) |
|---------------|---------|-------------------------------|--------------|------------|-------------|------------|
| 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 |

\[ \sum \text{Min}_i \text{CCI}_i = 0.1429 \]

\[ P = 7 \]

\[ N = 7 \]

\[ \sum CCI_i = 26.71 \]

\[ PCI = 54.39\% \]
6 Conclusions

Our study presents the development and application of a new modularization protocol mainly based on the MFD method and PCI metric. As a theoretical contribution, our paper developed some criteria to decide which modularization method would be the most useful. Our critical analysis in terms of the development phases to modularize the product (decomposition, integration, and assessment) may be used as a decision-making tool for modularization methods. The main contribution of 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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Declarations

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Consent to participate Not applicable.

Consent for publication All of the authors mentioned in the manuscript have agreed for authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.

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