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MODULAR FUNCTION DEPLOYMENT ADAPTED

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1. Introduction

Modularization has the potential to provide great benefits, but it is a task that must be planned considering the entire product's life cycle, since the form in which the division of product in modules is designed impacts on the resulting benefits experienced by the company [Holmqvist and Persson 2003]. Through modularization it is possible to reduce the internal variety and complexity [Daniilidis et al. 2012], offering a large external range of products to satisfy different market segments [Jose and Tollenaere 2005], reducing lead time and costs, increasing quality, and facilitating redesign [Daniilidis et al. 2011].

The interest in the development of modular products motivated the research and proposition of modularization methods and metrics [Gershenson et al. 2004], [Simpson et al. 2014]. The development of modular products demands more experience, coordination, effort and time from all departments. Since it takes into consideration the design of several products at once, modularization tends to be more expensive than the design of traditional products [Jose and Tollenaere 2005]. Modularization potentially promotes benefits to companies, but the division of products into modules is not a trivial task [Holmqvist and Persson 2003].

To aid in such process tools and methods have been proposed to guide modularization. In general, modularization methods aim at grouping components/subfunctions in modules according to similarities [Gershenson et al. 2004], although conceived from different departure points and targeted at different application areas [Daniilidis et al. 2011]. One of the most discussed methods in the literature is *Modular Function Deployment* – MFD, proposed by Erixon [1998]. MFD is a method based on the company's strategic objectives to carry out the modularization and implemented in five steps, ranging from surveying clients' requirements to the evaluation of resulting designs.

A study with companies that adopted the modularization strategy [Lau 2011] revealed that the reasons given by managers for not using formal methods are the difficulty in implementing and understanding them, in addition to the perception that a formal procedure may consume learning time and bureaucratize the development process. In such context, a flexible modularization methodology with an implementation difficulty level compatible with the development project's complexity should be useful.

Several projects are typically carried out simultaneously in a company's Product Development Process (PDP); their number and simultaneity depend on each company's capacity. Projects are temporary efforts undertaken for the creation of an exclusive product, service or result [PMBOK 2008]. Projects may present different characteristics, complexity degrees, and novelty levels. In the planning phase of PDP several viable projects are evaluated, and the ones approved to integrate the company's portfolio usually display different characteristics, specifications, development teams, and objectives.

According to Shenhar et al. [2005], one of the greatest mistakes related to project management in PDP is to consider all projects as similar and, consequently, demanding the same methods and techniques to

be managed. Product projects are likely to vary according to complexity and novelty level, among other characteristics. Matching project type to the project management approach is a critical factor for its success [Shenhar et al. 2005]. The same applies to the selection of modularization methods.
In this paper we propose an adaptation of the MFD method [Erixon 1998] to take into account different levels of complexity and novelty in product projects. The adaptation aims at helping companies to choose a method configuration that best adapts to the particularities of their product development projects and PDP. The adapted method, named *Modular Function Deployment Adapted* (MFDA), allows the possibility of choosing the set of stages and tools that best fits different combinations of complexity and novelty levels in a company's project, customizing the application to the type of project under analysis.

2. Background

In this section we review the literature on (*i*) modularization methods, and (*ii*) project typology.
Different techniques and methods have been proposed in the literature to assist companies to develop modular products. Studies show that adopting formal methods for identification and generation of modules significantly reduces time and resources compared to only using the know-how of development teams [Stewart and Yan 2008]. All methods for modularization require significant information input and data handling to obtain the desired result [Gershenson et al. 2004], [Booth et al. 2015]. The nature of such information and the complexity of calculations required may influence the choice of method by a particular company.
Methods for the product's modularization present similarities regarding phases to obtain a modular design, which may be used as a basis for a comparative analysis. In the literature review carried out in this study, six methods (see Table 1) were found and compared according to the proposition in Holmqvist and Persson [2003], to whom there are three critical phases in modularization: decomposition, integration, and evaluation. Methods were also analyzed in light of the framework proposed by Daniilidis et al. [2011] with respect to variety, generation, and life cycle parameters.
Holmqvist and Persson [2003] list three steps deemed critical to obtain modularity: decomposition of products in parts, integration of parts into modules, and evaluation of the resulting design. The six modularization methods available in the literature were analyzed regarding their proposed phases in order to elicit skills and knowledge required for their practical implementation. All methods presented similar propositions for the initial phase of product decomposition, but varied regarding strategies to integrate parts into modules in phase 2. Strategies varied according to the input information used for clustering of parts, as well as grouping algorithms. Four of the methods reviewed here present no formal procedures to evaluate designs resulting from the integration phase; yet, all methods suggest that designs should be evaluated and revised when necessary. Table 1 presents the methods, their objectives and procedures in each of the three critical steps to achieve modularization. Methods were also classified according to parameters of variety, generation, and life cycle used to characterize application areas and objectives [Daniilidis et al. 2011], as presented in Figure 1. In that figure, the groupings of methods and the parameters they encompass are identified by line styles. Methods did not present significant differences regarding classification parameters, mostly because they depart from a previously defined product architecture, which is required for the development of new products, to perform modularization. There was no differentiation of methods regarding variety since only those addressing individual products were chosen in our analysis, to assure that comparisons would only be made between methods dealing with the modularization problem at a same given level. The only parameter with respect to which methods presented some differences is life cycle, that considers product life aspects beyond its design.
After performing the analyses in Table 1 and Figure 1, the method chosen for adaptation was Erixon [1998]'s MFD. The reasons are: (i) the method is guided by the company's strategic objectives; (ii) it is complete, covering the three critical phases of the modularization process, and (iii) it is a self-documented method, since it is supported by several tools. Other benefits of MFD are the possibility of (i) high parallelism in the concept development phase, (ii) adopting statistical approaches to interpret the matrices used in the method, and (iii) incorporating both customers' and engineers' visions to the project [Borjesson 2009]. MFD drawbacks are high dependency on (i) the development team's expertise and (ii) the consistency of the scoring system [Borjesson 2009], [Kroll 2013].

Erixon [1998]'s original proposition consists of five steps, presented in Figure 2 and explained next. In step 1 (define customer requirements), QFD's house of quality [Akao 1990] is used to identify which product properties should be adjusted to meet customers' specific demands [Ericsson and Erixon 1999].

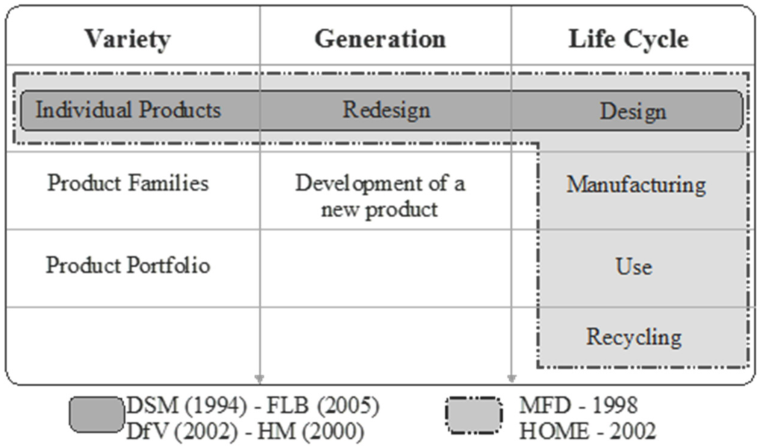

Figure 1. Methods classified according to parameters in Daniilidis et al. [2001]

In step 2 (select technical solutions) product's functions and subfunctions that enable the achieving of customers' demands (Step 1), and their corresponding technical solutions are identified. Later, technical solutions corresponding to product properties are determined through functional decomposition, which describe products by representation of functionalities [Pahl and Beitz 1996], [Roozenburg and Eekels 1995]. A review of functional decomposition methods is given by Booth et al. [2015].

In step 3 (generate concepts) grouping of technical solutions is performed according to pre-determined criteria, forming modules. This step is fundamental in MFD, since it is where modularization actually takes place. Technical solutions identified in step 2 are evaluated with respect to modularization guidelines listed in the MIM (Module Identification Matrix), using a 0 (no relationship) to 9 (strong relationship) scale. From this analysis technical solutions may either become independent modules or be grouped with other solutions. Erixon [1998] proposes 12 modularization guidelines; additional guidelines that reflect company's specific objectives and strategies may be also considered.

In step 4 (evaluate concepts) the interfaces matrix is used to make explicit the relations between modules and to evaluate them, pointing to critical and improvable interfaces. In this step tools related to economic issues, such as cost estimates for each module and their impact in the final product cost, may also be applied [Ericsson and Erixon 1999]. Erixon [1998] proposes metrics and rules by which aspects (e.g. quality, cost, and lead time) of the modular concept may be analyzed. The objective is to predict the impact of developing a modular architecture for the product under analysis.

In step 5 (improve each module) modules are optimized using methods such as Design for Assembly to ensure the quality of the final product, technical specifications sheets of modules are generated with the information from all MFD steps. The main objective here is to assure the efficiency of the final result.

Changes in the MFD method are available in the literature. The most significant was proposed by Borjesson [2009], who incorporates the Design Property Matrix in step 2 of the method, and recommends the use of cluster analysis on the MIM to identify modules.

The rest of this section is devoted to the subject of product typology, and corresponding relevant literature.

According to Tatikonda [1999], different project types have different characteristics, demanding specific planning and implementation approaches. Projects differ in many aspects and few organizations have acknowledged that formally, through the selection of suitable analytical approaches for each project [Shenhar et al. 2005]. In this paper, dimensions that differentiate projects will be considered; more specifically, we will focus on product complexity and novelty [Clark and Fujimoto 1992]. These dimensions may provide a good understanding of projects' characteristics and help to adapt management practices to specific project types (Table 2).

Table 1. Modularization methods according to critical steps proposed by Holmqvist and Persson [2003]

Method	Objectives	Decomposition	Integration	Evaluation
Design Structure Matrix – DSM [Pimmler and Eppinger 1994]	... finding alternative architectures in order to improve the quality of the resulting product design and to ease the substantial coordination demands that are required when sub-systems interact	Decomposition of system in elements	- Analysis of functional and physical interactions between elements - Identification of potential groupings	
Modular Function Deployment – MFD [Erixon 1998]	...achieve a modularization that not only complies to the company's expected improvements, and supports the individual company's selection drivers, but which also strengthens a company's ability to confront future expanding and deviating demands	- Definition of customers' requirements - Selection of technical solutions	Generation of concepts using the MIM matrix	- Evaluation of concepts using the Interfaces Matrix - Module improvement
Heuristic Method – 2000 [Stone et al. 2000]	... provide a systematic approach to identifying modules of a product from a functional model	Functional decomposition	Application of the heuristics (dominant flux, branched flux, conversion-transmission flux)	
Design for Variety – DfV [Martin and Ishii 2002]	...develop a decoupled architecture that requires less design effort for follow-on products	Generation of GVI (General Variety Index) and CI (Coupling Index) indexes	- Order components - Determine where to modularize (CI) and where to standardize (GVI) - Develop the architecture (components – functions/ interfaces)	
House of modular Improvement – HOME [Sand et al. 2002]	... develop a modular design method to address product life cycle concerns at the design stage	Information matrix of the modular design – Life cycle, architecture and functional requirements	EMIM Matrix – Grouping Algorithm	Analysis of the modular design
Fuzzy Logic Based – FLB [Nepal et al. 2005]	...optimizing the performance attributes of prospective modules while modularizing the product architecture early in the concept development phase	Process of knowledge acquisition (general analysis of the product – identification of the linguistic varieties, etc.)	- Fuzzy Inference - Mathematical model based on group technology algorithm	

Although viewed as a means to expand a company's market, modularization is likely to yield more complex products and related businesses [Blackenfelt 2001]. Complexity in products may be measured by the number of components and their connections [Blackenfelt 2001], [El Maraghy et al. 2012]. Presently, many products offered by companies are classified as complex, presenting variations that form product families which use a combination of different technologies, even presenting different solutions to the same function.

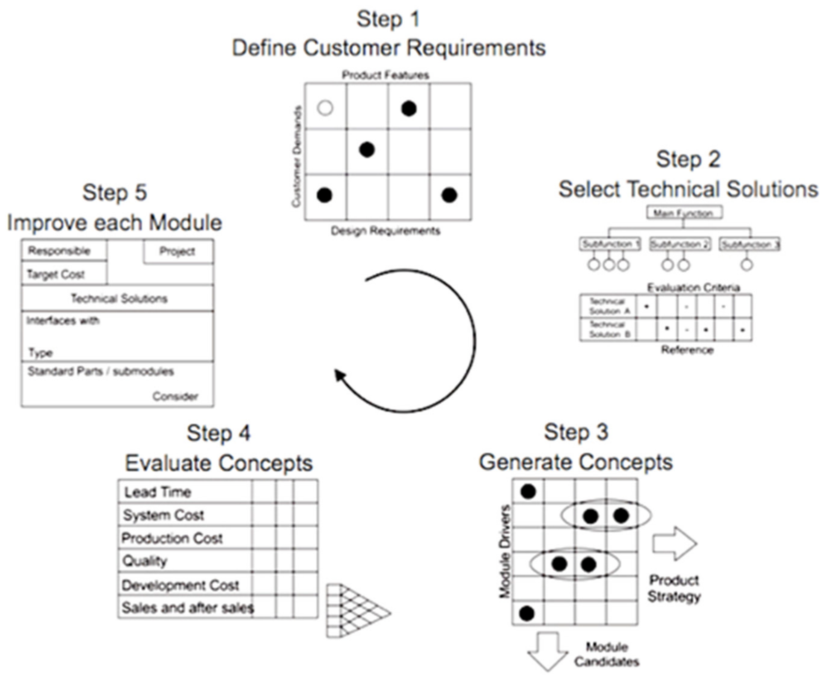

Figure 2. MFD operational steps

Holmqvist and Persson [2003] analyzed six modularization methods, focusing on their capacity to handle more complex products. In general, they found that the analyzed methods (among them MFD) were not designed to handle complexity. By contrast, Lau [2011] questioned whether modularization was a strategy targeted at high complex products, based on the fact that most of the literature only presented examples of modularized products manufactured by large companies.

In addition to complexity, novelty is also a dimension that influences project typology, for a product project may range from a simple improvement in existing models to 'new-to-the-world' products [Tidd and Bodley 2002]. When applying modularization methods the type of development – innovative design, improvement or derivative design – should also be considered [Blackenfelt 2001]. Yoon and Lilien [1985] propose two product typologies: original and reformulated. Original products represent technological advances that frequently depend on technologies never used before in the industry; they are also referred to as new product lines, or as new-to-the-world products. Reformulated products are extensions of existing lines or modifications. These modifications can reduce costs or increase usage possibilities, and are also named as improvements or additions. A product's novelty may be assessed according to the three levels described by Shenhar and Dvir [2004], which are similar to the ones by Pahl et al. [2007].

3. Research method and proposition

The proposition of MFDA (Modular Function Deployment Adapted) may be classified as prescriptive. Prescriptive representations tend to be focused on problems and based on suggestions for practical improvements, providing a detailed and systematic sequence of activities for practitioners to follow which are frequently represented by a linear progression, sometimes with feedback loops to indicate iterations [Pugh 1996 apud Moultrie et al. 2007].

Based on the analysis of the MFD method and changes proposed by other authors, we propose *Modular Function Deployment Adapted* – MFDA. We kept the original MFD steps, making adaptations and changes in the tools and procedures used in the first three method steps. They are reported next.

3.1 Define customer requirements

We divide this step in two main activities. The first aims at providing information about how much variety will be generated by the product, and is an improvement we propose to the method. The second activity uses the QFD matrix to relate customer demands to product features, as originally proposed by Erixon [1998].

Table 2. Variables for the complexity and novelty measurement in the product project

Complexity	· Size variation: there may be size differences between components as to the variation of products built on the same logic (more variation – more complexity) · Number of parts: the larger, the more complex a product is. · Technology: a product may use one or more technologies (more technologies – more complexity) · Number of variants: variants are different component combinations that may be substituted to create bottom-line products (more variants – more complexity) · Solution / function: there may be different technical solutions for the same function (different solutions – more complexity) · Architecture: relates to the way functions are allocated into modules (integral – more complexity / modular – less complexity)	Holmqvist and Persson [2003]
Novelty	· Derivative / Adaptive: corresponds to an improvement made in an existing product · Platform / Variant: corresponds to a new generation of an existing product line · Innovation / Original: corresponds to a new-to-the-world product (or, in this case, for the company).	Shenhar and Dvir [2004]; Pahl et al. [2007]

In the first activity, requirements are treated as to identify what is regarded by clients as (i) a product's differentiator or (ii) a basic feature. Requirements viewed as differentiators by the clients point to solutions/components of the product which should be worked to deliver variety to clients according to their needs. We propose identifying them through a quantitative questionnaire in which consumers assign an importance score to each product requirement demanded. Such approach follows the proposition in Jiao and Tseng [1999], in which functional requirements of the product are categorized in groups that characterize customers' segments. Their analysis allows to quantify the relative importance of each requirement, separating them in two groups: the ones depending on the segment (items regarded as highly important and perceived as having a higher value by customers), and the ones that can be present in all product variants [Jiao and Tseng 1999].

3.2 Select technical solutions

In this step, the DPM matrix is used to relate technical solutions to product properties. Technical solutions are determined through a functional decomposition method [Roozenburg and Eekels 1995], [Pahl and Beitz 1996], such as illustrated in Figure 3. If more than one technical solution provides a certain product function, we recommend using Pugh's Matrix [Pugh 1991] to select the best one. The DPM matrix in Figure 5 aims at quantifying the importance of the proposed technical solutions, following the rationale of the quality matrix used in the first step.

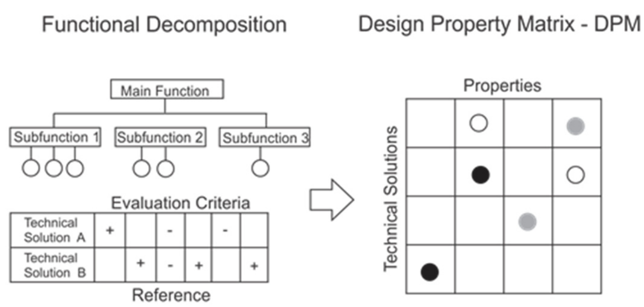

Figure 3. Select technical solutions

3.3 Generate concepts

In this step, deemed crucial in MFD, technical solutions are grouped into modules. Two different approaches are proposed for that, depending on the degree of product complexity.

For low complexity products we recommend the use of Erixon [1998]'s traditional approach, in which technical solutions with higher scores become modules while those with lower scores are integrated into existing modules according to similarities displayed in the MIM matrix. Such similarities are identified by summing scores that measure the relation of technical solutions with guidelines (Figure 4).

Modularization guidelines are the strategic objectives identified by companies when modularizing their products. Since modularization guidelines may not lead to the same structural solution, the development team may need to reevaluate solutions analyzing conflicts between requirements. One may weigh guidelines according to the project, emphasizing its important aspects. Requirement prioritization is in conformity with the approach by Seliger and Zettl [2008], in which it is assumed that some guidelines are more important than others in the modularization process.

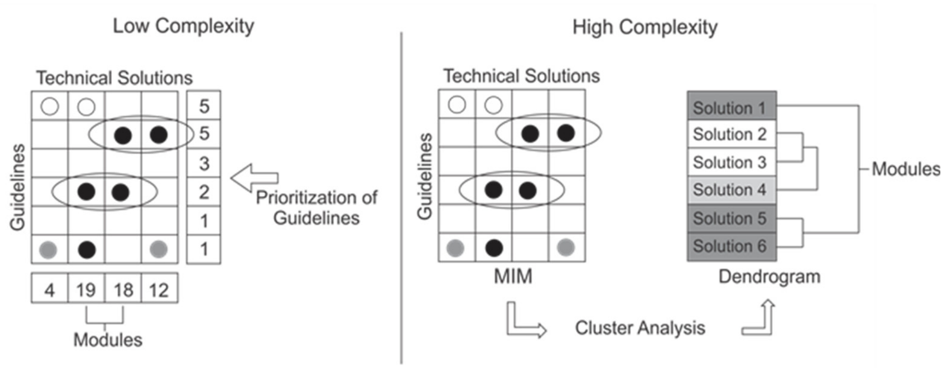

Figure 4. Concept generation for low and high complexity products

For high complexity products it is suggested to use cluster analysis to identify modules, aligned with the proposition in Borjesson [2009]. Due to the large number of components that characterizes complex products the scoring approach described above may lead to a large number of solutions to be analyzed, and a cluster analysis approach becomes the more reasonable course of actions. In the analysis, clustering variables are the guidelines and their importance scores, and objects are the components or parts which will be grouped by similarity, indicating possible modules.

4. Discussion

The MFD method was adapted to accommodate two dimensions that differentiate products: their complexity degree and novelty level (see Figure 5). Complexity relates to how information in the MIM matrix will be handled. In case of complex products interpreting the information in the MIM calls for multivariate statistical techniques; otherwise, the original interpretation proposition is the best course of action. Novelty affects the selection of activities/steps to be used in the MFD method. High novelty projects call for the use of MFD with all its steps, while low novelty projects, which are usually characterized by improvement of existing projects in which clients' requirements are known and technical solutions are already established, waive the need for the first two steps in MFD in most instances. As mentioned by Lau [2011], managers of small companies do not use modularization methods due to their complexity. Thus, the proposition of an adapted method that takes into account the existence of low novelty projects may be useful to companies aiming at optimizing their scarse resources.

In Figure 5, the matrix to the left represents the different levels of complexity and novelty that a company's projects may display. Limits of each cell in that matrix are defined analyzing the variables presented in Table 2. The development team selects the cell that best represents the characteristics of the project at hand. Four different MFDA configurations follow from the choice of cell (only high/low level combinations are considered). Each configuration considers different complexity and novelty degrees of the product, leading to a different sequence of modularization steps and supporting tools. Note that configurations derive exclusively from combinations of high and low levels of complexity and novelty, which is one of the method's limitations.

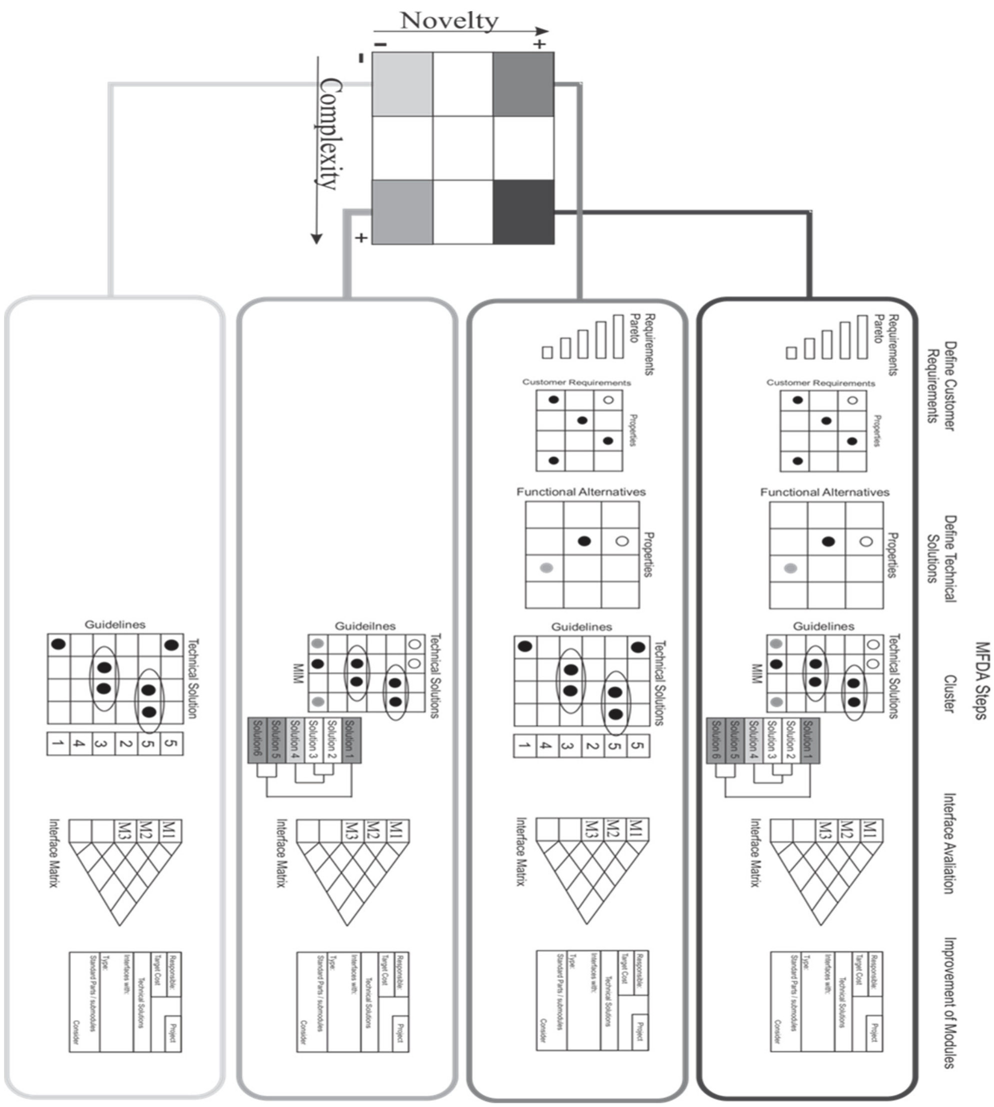

Figure 5. Four different MFDA configurations, according to complexity and novelty levels of projects

5. Conclusions and future research

In this paper we proposed an adaptation of MFD method that accounts for projects with different complexity and novelty levels. The adaptation aims at facilitating MFD's practical implementation, by allowing companies to choose the method configuration that best suits their specific needs.

Our proposition was derived from a study carried out in three steps: literature review, with the objective of analyzing the modularization methods proposed in the literature and choose the one most suitable to our purposes; literature review on the chosen method, identifying its applications, benefits, and improvements as suggested by other authors; and semi-structured interviews with MFD experts from companies, to gather information on the method's state-of-the-practice. Based on the information from these sources, we proposed the MFDA method.

In addition to adapting the MFD method to accommodate projects with different levels of complexity and novelty, we also proposed changes in two of the method's steps, aiming at facilitating the interpretation of the MIM, which is the matrix that guides the modularization process.

The proposal of an adapted MFD calls for further analysis of its usability in practice. The study of modularization guidelines is another research opportunity, as the quality of the modularization process relies on guidelines chosen by the company to lead the grouping of parts into modules.

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