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LEAN MORPHOLOGICAL MATRIX: A NEW APPROACH FOR CONCEPTS DEVELOPMENT

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Abstract. *The purpose of this research is to provide a discussion about the Morphological Matrix tool, a model that is used inside the Conceptual Project Phase of PRODIP Product Development Methodology. In this Phase, the Morphological Matrix is applied in order to design distinct concepts for the desired product. A concept is a cluster of possible solution principles, which must be aligned to the project requirements and customer demand. Both are defined during the Informational Project Phase. All proposed concepts are evaluated aiming to establish the best concept for the product. Therefore, the Conceptual Phase is performed on main decisions about the product configuration, becoming one of the most critical phases in a project development. For complex products, the large number of elementary functions and solution principles drives to a combinatorial explosion and the development of all possible concepts becomes impracticable. As a result, this research proposes a methodology to reduce the number of elements in the Morphological Matrix, through the prioritization of elementary functions that are most relevant to the development of the basic physical concept of the product. Thereby, it is possible to develop and evaluate basic physical concepts and from them work with the remaining elementary functions. This method was assigned as Lean Morphological Matrix. The prioritization task is ruled by predefined criteria, such as the relative importance of the project requirements, the Quality Function Deployment definitions and the correlation between elementary functions. A case study is performed for the project of a robotic platform for a specific cargo transportation, a project owned by CELESC - Centrais Elétricas de Santa Catarina S.A. and developed by the Laboratory of Applied Robotics from UFSC. This work contributes to the optimization of the PRODIP methodology and aims to ensure the excellence of a critical phase during a project development, the Conceptual Project Phase.*

Keywords: *Morphological Matrix, Conceptual Project, Product Development*

1. INTRODUCTION

The engineering design process requires an approach that enables converting a cluster of objectives into a product that accomplishes customers and project requirements. Furthermore, the modern industry demands agile and cost-effective tools to perform this approach the best possible way. Aiming to achieve these objectives, a lot of research in the field of product development has been done to optimize the actual approaches, these researches include technological improvements, such as modeling and simulation tools, and methodology optimization.

These new techniques led to a significant improvement on engineering design, even on the Conceptual Phase, when the development of the first concept of the product occurs. The Conceptual Phase is performed on the main decisions about the product configuration, quality, efficiency and cost, becoming one of the most critical phases during product development. Furthermore, according to Hui *et al.* (2006), the Conceptual Design takes only 5% of the total development cost, but it is responsible for deciding 70% cost of the product, enhancing the importance of this phase.

However, most of the generated concepts are modifications of already existing products, therefore, the development of tools to solve this issue must be a concern of designers. As a result, a great diversity of authors proposed different tools to facilitate the concept generation phase, among these methods are the 'black box' proposed by Pahl and Beitz (2013), the Theory of Inventive Problem Solving by Altshuller (1984), and the PRODIP approach (Back *et al.*, 2008), that utilizes the morphological matrix, which is the main focus of this research.

The morphological matrix is composed by a vertical axis containing the main functions performed by the product, these functions are defined based on project requirements and customer demand, which were established during the Informational Project Phase. On the horizontal axis are listed all possible solution principles.

This tool's strength is the possibility of generating a big amount of concepts, increasing the potential of innovation due to the possibility of combining each principle of solution of a function between other functions' solution principles. Otherwise, when dealing with a complex product, this tool strength is also its fragility, the large amount of possible combinations leads to a combinatorial explosion, becoming impractical to analyze all possible concepts as discussed by Motte and Bjärnemo (2013).

2. CONCEPTUAL PHASE

There are methods validated in the literature for the development of projects (Pahl and Beitz (2013); Ulrich and Eppinger (1995); Back *et al.* (2008)), which are formed by several phases and stages of development as discussed by Romano (2003). Regardless of the method or set of methods chosen for its development, every project of a new product goes through a stage of conception generation, where the innovation and effectiveness of the developed product is the focus.

Based on Rozenfeld and Amaral (2006) Product Development can be seen as a set of activities through which it is possible to achieve the project specifications of a product, taking into account customer requisites, technological constraints and competitive strategies. According to Hoffmeister *et al.* (2003), the product design cannot be based on empiricism and in intuition, but it must be based on solid methods, which have a scientific basis.

The engineering design process can be divided into four main sequential phases, according to the Systematic Approach proposed by Pahl and Beitz (2013), which are: Task Clarification, Conceptual Design, Embodiment Design, and Detail Design. The Task Clarification phase is when all the requirements and demands are formulated, aiming to accomplish the objective of the product. During the Conceptual Design, the first sketches and models about the product are developed. The Embodiment Design phase is responsible for selecting and detailing the layout of the most promising concepts. Finally, the Detail Design is responsible for analyzing all components of the product, evaluating which solution is the best and preparing the manufacturing documents.

As proposed, all the stages are executed sequentially and iteratively, thus, it is evident the influence of each phase on the final product. Aiming to ensure the quality of the method, Pahl and Beitz proposed a "decision-making step" between the phases, when the results of a phase are analysed and it is decided whether the next phase can be started or whether the phase must be redone.

Furthermore, each step of the method has a relative weight corresponding with its importance on the final product, meaning that some phases are more significant and critical during the engineering design process. For example, it is evident the importance of the Conceptual Phase during the project, because the results of this step influence on Embodiment and Detail Design, thus the development of the product only increases in cost and time once there is not a completed and solid concept's generation phase.

In the Conceptual Phase of a research, development and innovation project, the engineers work to design innovative concepts that solve the main problem, these concepts must be aligned with customers demands and project requirements. In an early stage of this phase, the engineers focus on conceptual ideas which present high potential to achieve the project goal, usually setting aside details of dimensional aspects, the cost and technical ability of the team to develop the concept, this approach enables the designers to quickly modify the concepts without great effort.

After the early stage of concept generation, it is possible to identify the design limitations and viability, predict the cost and time of development, and draw conclusions about whether the product is innovative and marketable.

2.1 PRODIP APPROACH

The PRODIP methodology proposed by Back *et al.* (2008), is divided into three main stages: planning, design and implementation. In the planning stage, the product planning and project planning are defined. In product planning, the goal is to define product ideas that will be developed subsequently. The design stage is divided into four phases: Informational Design, Conceptual Design, Preliminary Design and Detailed Design. In the Informational Design phase the design specifications and the degree of importance for each specification are established. The main method employed is the House of Quality Matrix of the Quality Function Deployment (QFD) methodology.

The alternatives generated are evaluated according to economic and viability criteria, from which the best solutions to the problem are selected. The method used in this phase is the technological mapping. In the project planning the plan for the development of the selected product ideas is established.

The Conceptual Design Phase is characterized by the creative moment. The concepts generated in this phase are evaluated according to economic and viability criteria, from which the best solutions to the main problem are selected. The methods employed in this phase are: multicriteria matrices of selection, synthesis of functions and morphological matrix.

The preliminary design phase aims to define the product layout, arrangement, shapes, geometry, materials and manufacturing processes are also outlined in this phase. The main tools employed are: analysis models, simulation, optimization and pilot prototype construction. In the last phase of the design stage, the detailed phase of the project takes place. At this moment the final technical drawings and the material list are produced at the highest degree of detail for the manufacture of the product, in addition to the development of manuals and catalogs. The implementation stage is divided into: production preparation, product release and validation. In the production preparation phase, the documentation of assembly, purchase of material, construction of the tooling, preparation of the machines, implementation of the production line and finally the release of the product to the initial batch are prepared. In the launch phase the product is launched on the market. Finally in the validation phase, products are monitored in the market and evaluated with users.

In this work, the Conceptual Design Phase is presented with a greater degree of detail, the tool used is the Morphological Matrix. In the Morphological Matrix, each line corresponds to an elementary function and its solution principles, where each principle fills a different column of the matrix, in its respective line. The matrix is developed from the elementary functions and its respective solution principles. Thus, each line shows all the solution principles found for a given elementary function. The generation of the solution principles will define the technical possibilities of operation of the product.

During the application of the Morphological Matrix in complex projects, some limitations can be found. This limitation occurs due to the expressive number of elementary functions and the different solution principles for each one of them. In this regard, the explosive combinatorial possibilities to obtain a conception become complex and exhausting as discussed by Motte and Bjärnemo (2013). Seeking an alternative to the problem, this work proposes a tool for prioritizing elementary functions, in Fig. 1 the flowchart shows where the improvement will be implemented.

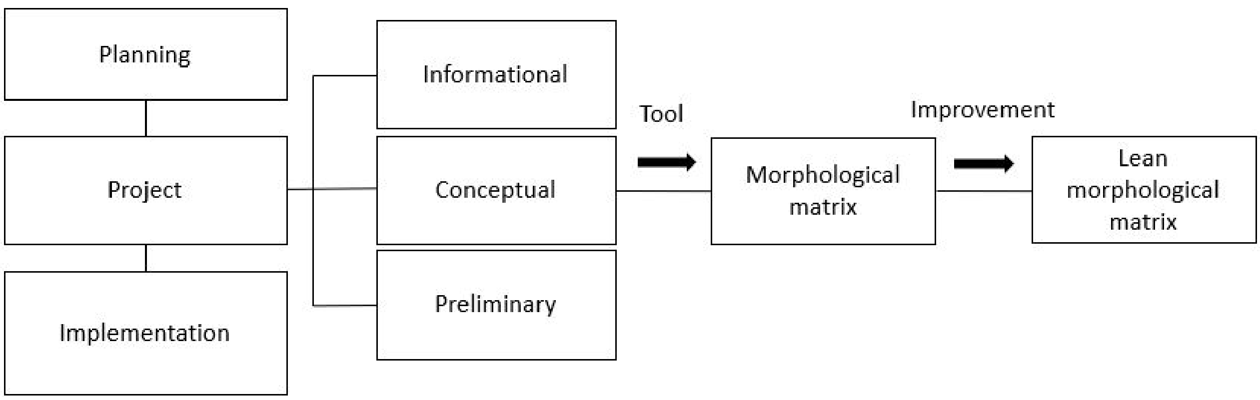

Figure 1. Schematic flowchart of the proposed improvement site within the conceptual design phase.

The function prioritization process is based on the functions that delimit the main goal of the product, in the proposed tool the functions not chosen to form the Lean Morphological Matrix are treated as support functions and receive special care at a later stage of the Conceptual Phase.

3. LEAN MORPHOLOGICAL MATRIX - LMM

The research, development and innovation project in which the present study was applied is under development since 2019 as a result of a partnership between the company *Centrais Elétricas de Santa Catarina S.A* (CELESC) and the Laboratory of Applied Robotics (LAR) of the *Universidade Federal de Santa Catarina* (UFSC). The project aims to develop a robotic platform for a specific cargo transportation in hard-to-reach locations.

The project has been developed in accordance with the methodology provided by Back *et al.* (2008) which is based in the research and teaching experience of the Core of Integrated Product Development (in portuguese *Núcleo de Desenvolvimento Integrado de Produtos - NeDIP*) of UFSC since 1970.

During early stages of the Conceptual Phase, global functions, partial functions and elementary functions were established. Then groups of solutions were generated for each elementary function creating the Morphological Matrix. In the presented case the Morphological Matrix consisted of 54 elementary functions totaling over 300 possible solution principles.

Due to the magnitude of the achieved Morphological Matrix there was a combinatorial explosion among the possible solutions to all elementary functions, resulting in an impracticable phase of design generation. In this regard a different approach was established and titled as *Lean Morphological Matrix - LMM*.

The LMM aims to decrease the possible combinations between the solutions of elementary functions by dividing them into protagonist groups. The protagonist group is formed by elementary functions that have a greater impact on the dimensions and solutions that shape the project design, resulting in a group of initial conceptual designs meeting the elementary functions contained in the LMM. This process is shown in Fig. 2.

In order to establish the elementary functions that form the LMM, it is necessary to analyze which elementary functions present a greater conceptual impact in the resolution of the global function of the project. Among these, it is also necessary to identify which ones present related solutions, known as Theory of Coupling discussed by Weber and Condoor (1998).

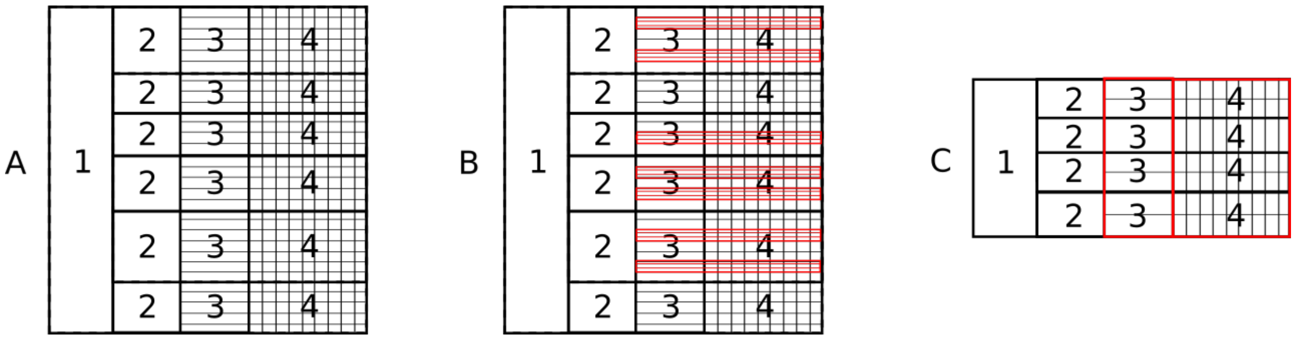

Figure 2. Protagonists group of elementary functions (B) obtained from the initial Morphological Matrix (A) form the Lean Morphological Matrix (C), where 1 - global function, 2 - partial functions, 3 - elementary functions and 4 - solution principles.

Thus, from the initial conceptual designs, the solutions proposed for the remaining elementary functions would pass through a similar stage and would then be aggregated, resulting in a complete conceptual design that meets all elementary functions. In the meantime, during the development of the complementary LMM, it is possible to start the Preliminary Project Phase by detailing and developing the chosen conceptual designs.

3.1 METHOD EVALUATION

Being a complex project, the Morphological Matrix of the Robotic Platform Project was composed of one global function, six partial functions and fifty-four elementary functions. The biggest challenges in the project regard the product dimensions. The final product design shall be compact enough to maneuver in corridors and confined locations. It must also carry different sizes of cargo and overcome different obstacles presented in the path.

As the biggest challenges are related to the dimensions of the final product, initial considerations were made regarding the selection of elementary functions to constitute the LMM. In an early stage, all functions connected to solutions aimed at control, sensing and accessories were removed from the initial Morphological Matrix, resulting in a group of three partial functions (PF) and thirty-four elementary functions (EF). From this stage onwards another line of reasoning was followed.

The second stage of analysis took into account the relationship between the choice of solution principles for elementary functions and the conceptual impact on the proposals of future conceptions. To clarify, an example of a drive system will be presented, highlighting probable situations discussed during this stage.

The PF and EF of a drive system project is given in Tab. 1. In a early stage of the given example the EF related to control can be removed from the Morphological Matrix, *Fuel/energy sensor* respectively, since is not tangible and depends on the choice of solution of other EF, presenting low impact in the idea and shape of a possible conception.

In a second stage, analyzing the elementary functions *Recharge*, *Store the energy*, *Stop/maintain power of the drive system* and *Transform energy*. The four elementary functions are related to the type of energy source chosen for the vehicle (combustion, electrical, hydraulic or pneumatic) and when defining the energy source (elementary function *Transform energy*) the other three solutions concerning the other three elementary functions are also already defined. The same three functions concern the solutions of being rechargeable, the kind of energy storage (fuel tank, batteries and others) and the start system, respectively, presenting a low impact on shaping possible solutions for the partial function *Move the vehicle* when compared to functions involving steering system and motion execution as solution principles. Thus, for this situation it is decided to keep as protagonist the elementary function *Transform energy*.

A second situation involves the elementary functions *Perform movements*, *Guiding mechanism* and *Move linearly back and forth*. The functions *Perform movements* and *Guiding mechanism* are related to the choice of solution principles

Table 1. Example of early stage group of elementary functions in a drive system project.

Partial Function	**Elementary Functions**
Move the vehicle	Recharge Store the energy Fuel/energy sensor Stop/maintain power of the drive system Transform energy Transmit energy Perform movements Guiding mechanism Move linearly back and forth Drive the mechanism to reduce speed Reduce speed (service brake) Redundancy in the braking system Dampen vibrations

for the final effector of movements (wheels, treads, arms or others) and the type of the steering system (mechanical, electrical, hydrostatic or others), respectively. On the other hand, the function *Move linearly back and forth* is related to solutions found in machine elements or engine rotation inversion. Therefore, in this situation, for the initial stage of conceptions generation, the functions *Perform movements* and *Guiding mechanism* were defined as protagonists and the function *Move linearly back and forth* was not, since it is dependent on the choice made in other elementary functions and has a lower impact on the choice of solutions for the development of initial conceptions.

The same logic is applied to the EF *Drive the mechanism to reduce speed*, *Reduce speed (service brake)* and *Redundancy in the braking system*. The first is related to the brake interface and the second and third are directly related in the possible choices of brakes. For this reason the EF *Reduce speed (service brake)* and *Redundancy in the braking system* were defined as protagonists.

Regarding the EF *Dampen vibrations* the function present solutions related to types of dampers and materials choice in order to diminish vibration, improving the useful life of mechanical components and decreasing the noise during the vehicle operation. In a first conceptual phase this EF was not defined as protagonist, hence it depends on the choices of other functions and does not have an impact on the general idea of the initial conception design.

Finally, after analysing all EF, the Lean Morphological Matrix is formed Tab. 2 to enable the development of different early stage conceptual designs.

Table 2. Example of Lean Morphological Matrix Elementary functions in a drive system project.

Partial Funtion	**Elementary Functions**
Move the vehicle	Transform energy Transmit energy Perform movements Guiding mechanism Reduce speed (service brake) Redundancy in the braking system

The reasoning presented in the discussed example was applied in the Robotic Platform Project. The analysis was performed in all elementary functions, relating them according to their solution principles and defining the protagonists according to the impact on the conceptual design of the product. This analysis resulted into elementary functions and their respective solution principles that formed the Lean Morphological Matrix. This process reduced the number of EF from 54 to 15 protagonists, enabling innovative ideas in the initial conception generation, greatly reducing the total number of possible solutions among the Elementary Functions, eliminating the possibility of combinatorial explosion.

4. RESULTS AND DISCUSSION

As a result proposed and applied we have an initial method to form the Lean Morphological Matrix which facilitates the generation of conceptions in complex research, development and innovation projects. The method of the LMM proposes to focus first on the biggest challenges of the product in development presenting a general concept of solution, enabling innovation and then aggregate all the solutions for the remaining elementary functions presented in the initial Morphological Matrix.

By applying the proposed method in the Robotic Platform Project it was possible to validate the method by analyzing whether the protagonist group was correctly defined.

During the development of the conceptions to the presented case, the team verified that the elementary functions that form the LMM were sufficient for the generation of initial conceptual designs, but it was also possible to observe that some of them might not be part of this group. In the drive system case, functions *Transform energy*, *Reduce speed (service brake)* and *Redundancy in the braking system*, which presents the solutions for the type of fuel to the propulsion system and the types of brake, may be adapted and modified in any conceptual design developed without impacting the concept of the design solution for the global function. Thus the team identified that to define the solutions for these elementary functions an analysis with calculations of power and weight are more indicated, which can be done in later stages of the project.

The Robotic Platform Project is still in progress, but it is already possible to observe the benefits that the Lean Morphological Matrix brought to the stage of conception generation. Among the benefits it is possible to highlight the advantage of not generating an explosion of combined solutions, which results in time and cost optimization and enables the generation of innovative concepts. The team focused more on solving the main problems of the project presenting more innovative ideas in a lower level of mechanical details, but already enabling the analysis of the feasibility of each design.

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