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A SYSTEMATIC APPROACH FOR RELATIONSHIPS ANALYSIS OF MORPHOLOGICAL MATRIX SOLUTION PRINCIPLES

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Abstract. *In the Conceptual Design Phase of the Integrated Product Development Process (PRODIP) Methodology, conceptual solutions for a new product, or the improvement of an existing one, are developed combining the principles of solution for the product's functions. They are arranged inside different concepts, using a Morphological Matrix. However, as the number of solution principles increases, a combinatorial explosion of the Morphological Matrix may occur, making technical and economic evaluation difficult. This paper presents a systematic approach for determining and exposing the types of relationship between all the functions and also all the principles of solution. Using a robotic platform as a case study, a matrix was developed to showcase the types of existing relationships and the implications of each choice of a specific principle of solution. The result of this approach aided the visualization of which solution principles are not compatible or exhibit a beneficial preference. At the end of the analysis, 394 restraint relations, 165 obligation relations and 626 benefit relations were selected. In addition to decreasing the number of combinations, this proposal identified for evaluation four elementary functions that have a greater impact on the task of creating concepts, improving the creative process.*

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

1. INTRODUCTION

From the perspective of a globalized market, the creation of products is increasingly competitive and the competition of several companies generates the need for constant innovations. These companies seek to distinguish themselves from their competitors and create more innovative products through internal development factors. Thus, in a company that produces goods or products, it is fundamental that quality must be integrated into the product throughout its life cycle, as the industrial product development process covers several stages, from the activity of identifying needs to the final disposal. For the product design, design methodologies represent advantages such as the reduction of product development time, reduction of design modifications and increase of quality under several aspects (Back et al. 2008).

The Federal University of Santa Catarina (UFSC), attending to this demand, aims to develop excellent product development and design methodologies, especially through the Integrated Product Development Process (PRODIP), which was developed at NeDIP/EMC/UFSC. With a modern approach to simultaneous engineering, the methodology contemplates aspects of product planning and design in general, from market research to product deactivation. PRODIP is composed of objectives, methods, tools and activities provide the team with a systematic way of development for a new product or the improvement of an existing one, aiming to obtain a final result desired to the participants of the process and, later and mainly, to the users of the product (Back et al., 2008; Melo and Ogliari, 2015).

Included in the second macro-phrase (design), as shown in the following topic, the conceptual project is the design stage defined by establishing the product conception, i.e., which is the most suitable product to solve the needs of the product user. The conceptual design of a product must be well elaborated from the beginning to avoid high modification costs in advanced stages of development (Huthwaite and Schneberger, 1992 apud Back et al., 2008). Throughout the process, function (tasks that are performed), working principles (such as types of energy and physical affects) and the embodiment (shape, size, scale) are examined closely to find development opportunities and meet requirements (Pahl et al. 2006).

To do this, the design team aims to generate several conceptions that meet the defined specifications. All those solutions are then gathered in a Morphological Chart, to achieve a “systematic approach”, as described by Pahl *et al.* (2006). This approach allows for the composed ideas to happen through a longer interval, and the propositions to be organized and available for selection at a later time.

Following, the morphological matrix method consists of a systematic search for different combinations of elements or parameters, with the aim of finding a new solution to the problem. Thus, the morphological matrix is primarily aimed at gathering an exhaustive set of solutions to a given problem by decomposing it into subproblems, finding solutions for each subproblem, and combining them.

The strength of the method, its ability to propose a large number of solutions, is also its Achilles heel: it has the well-known disadvantage of a combinatorial explosion. The number of possible combinations increases exponentially with the number of solutions proposed for each subproblem (Motte and Bjärnemo 2014). To deal with this problem, several methods were created, as for example the Motte Heuristic Methods, the cross-compatibility matrix shows promise: besides decreasing the number of designs, it serves as an analysis of the design creation process (Pahl *et al.* 2006). An optimal solution will fulfill all demands in the requirements list as well as most of the wishes and can be realized by the company within the constraints of budget and feasibility. According to Back *et al.* (2008) many designs can be eliminated immediately for not being compatible or feasible. Both statements can help slim the morphological matrix and allow for a more direct, efficient and effective search of the solution. Considering the presented object, our matrix was then developed as presented in this document to achieve these solutions faster and in the most effective way possible, and this document aims to describe the tools and process used so that other teams can replicate these results.

Furthermore, the numbers of relationships found were used to determine which elementary functions can be selected for a technical and economic analysis without using functions that do not impact the creation of the concept.

2. PRODIP CONCEPTUAL PHASE

The Integrated Product Development Process (PRODIP), proposed by Back *et al.* (2008), is divided into three macro phases: planning, design and implementation (Figure 1).

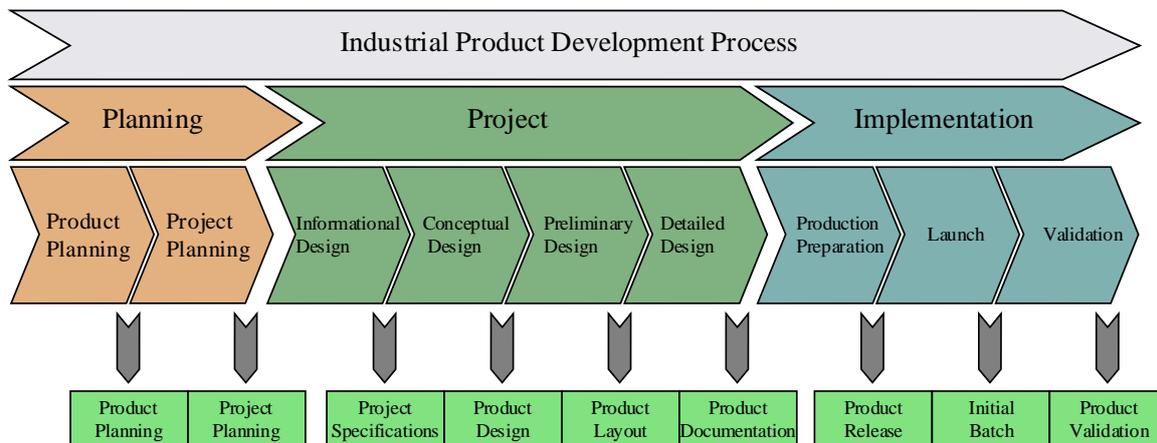


Figure 1 - PRODIP Methodology (adapted from BACK *et al.*, 2008)

The Planning macro phase is subdivided into two new phases: Product Planning and Project Planning. At this stage, it is defined as product ideas to be developed in a given period of time and the plan for their development.

The Project macro phase is subdivided into four phases: Informational Design, Conceptual Design, Preliminary Design and Detailed Design. In the Informational Design, the project specifications and their degree of importance are established; in Conceptual Design, the search for conceptual solutions to the problem is carried out. The main tools used in this step are function synthesis, morphological matrix, and multi-criteria selection matrices; in the Preliminary Design, the conceptual solution is developed; in the Detailed Design, the optimized solution is tested and finalized.

The Implementation macro phase is subdivided into Production preparation, Launch, and Validation, which together will define how the product will join and how it will stay on the market.

As it is completely aligned with the proposal of this work, the Conceptual Phase will be addressed in greater depth. This phase provides as outputs the conceptions that satisfy the project specifications, defined in the previous steps. For this to occur, it is necessary to establish a functional structure of the product.

The Functional Synthesis Method, developed by Koller (1985) and improved by Pahl *et al.* (2006) is constituted by a Global Function, which in turn is divided directly into Subfunctions (partial functions) corresponding to the subtasks. From the Subfunctions, it is possible to obtain the so-called Elementary Functions (Figure 2).

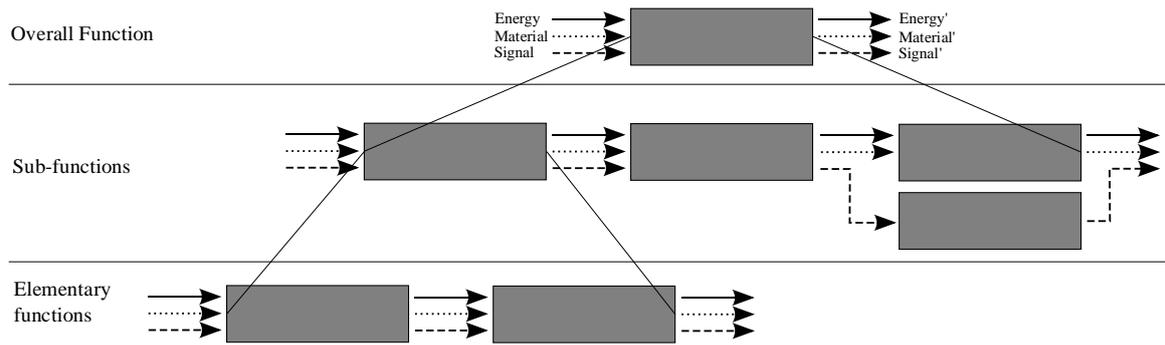


Figure 2 - Establishing a function structure by breaking down an overall function into elementary functions (adapted from Pahl *et al.*, 2006).

The relationship between Subfunctions and the Global Function is often governed by certain constraints, as some Subfunctions must be satisfied before others. One of the tools used to generate solutions is through the Morphological Matrix. In it, each line shows all the solution principles found for a given elementary function. For each elementary function, different principles of solutions fill a different column of the matrix.

With a full morphological matrix, the elementary functions are crossed to define how they interrelate. This interrelationship is under the perspective of choice, in the sense of how the choice of a solution principle interferes, obliges, or prevents the choice of the remainder of the set of principles. Thus, by studying the elementary functions of the Morphological Matrix and conducting an relationship analysis between the solution principles, decisions that have the greatest impact on the process of creating concepts can be identified.

3. RELATIONSHIP ANALYSIS

A recommended method for reducing the number of combinations is the search for incompatibilities between the solution principles by comparing the compatibility of the principles in pairs, this technique is sometimes called a compatibility matrix or a cross coherence assessment (Ritchey, 2006 apud Motte and Björnemo, 2014; Pahl *et al.*, 2006). This method was used and expanded, and is referenced to here as Relationship Analysis. Along the search for incompatibilities, pairs of solution principles that are not only compatible but also have an advantage in comparison to the others were sought.

A Boolean matrix was used for the Relationship Analysis. The Boolean matrix indicates the presence of the relationship of its lines with the columns through Boolean elements 0 or 1. The direction of the relationships is from the principle of solution situated in the line to the principle located in the column. Thus, the value 0 means that the line solution principle is not related to the column solution principle, while the value 1 indicates the relationship between them.

An example can be seen in Figure 3, where the relationships of the lines containing the solution principles of the elementary function "Store the energy to the system" with the columns containing the solution principles of the elementary function "Transform the energy to the system" were verified.

It is observed that the choice of battery use is related to the choice of transforming the energy to the system using mechanical systems. This means that there are consequences resulting from the selection of the solution principle of the elementary function "Store the energy to the system" in the process of choosing the solution principle of the elementary function "Transform the energy to the system", as in case there were no relationship, the whole matrix would have to be filled with the value 0.

	Mechanical Systems	Electrical Systems	Hydraulic Systems	Pneumatic Systems	Not Transform
Fuel Tank	0	1	0	0	0
Flywheel	0	1	0	0	0
Battery	1	1	0	0	0
Supercapacitor	1	1	0	0	0
Hydraulic Accumulator	0	1	1	1	0
Air Pressure Vessel	0	1	1	1	0

Figure 3 - Boolean matrix that determines relationship existence.

The type of relationship was considered for the analysis. There are cases in which some combinations of solution principles, in the view of the designer, are encouraged, such as where their choice can meet two elementary functions. In this way, it is valuable to recognize the principles that produce the most beneficial relationships. To incorporate information from the different relationship types in the Boolean matrix, four symbols were added:

- The symbol **B** represents the "Benefit" relation of the combined use of two solution principles and also the possibility of choosing the same solution principle for distinct elementary functions, as the solution of two elementary functions by the same principle of solution represents a beneficial relationship.
- The symbol **X** represents that the choice of this solution principle restricts the choice of a second principle.
- The symbol **O** represents that the choice of a "binding" principle to a single possible choice of principle in another function, which is an extension of the restriction relation symbolized by **X**.
- The symbol **0** continues to represent the non-relationship between the solution principles.

The example previously shown in Figure 3 can be visualized with their respective relationship types in Figure 4, where it is possible to verify that the choice of battery use, similar to the supercapacitor, restricts the choice of transforming the energy to the system using mechanical systems benefits from the design with joint choice with the electrical systems and does not restrict the choice of the use of the hydraulic assembly to create this design.

	Mechanical Systems	Electrical Systems	Hydraulic Systems	Pneumatic Systems	Not Transform
Fuel Tank	0	X	0	0	0
Flywheel	0	X	0	0	0
Battery	X	B	0	0	0
Supercapacitor	X	B	0	0	0
Hydraulic Accumulator	O	X	B	X	0
Air Pressure Vessel	O	X	X	B	0

Figure 4 – Boolean matrix that determines the existence and types of relationships

The procedure of using the Morphological Matrix determines that in the elaboration of conceptions, only one solution principle for each elementary function can be chosen (Back et al. 2008; Pahl et al. 2006). Thus, the relation of an elementary function to itself exposes this logic of obligatory. This effect is exemplified in Figure 5 through the elementary function "Transforming electrical energy to mechanical". The figure also presents the equality of the restriction relation **X** with the obligatory relation **O**.

	Electric Motor	Electro-mechanical Actuator	Electromagnet		Electric Motor	Electro-mechanical Actuator	Electromagnet
Electric Motor	0	X	X	=	O	O	O
Electro-mechanical Actuator	X	O	X		0	O	O
Electromagnet	X	X	O		0	O	O

Figure 5 - Equality of restriction and obligation

By using this set of rules, it is possible to perform the individual analysis of the relationships of each solution principle of the Morphological Matrix, producing a Relationship Matrix containing all combinations of possible choices. From the Relationship Matrix, it is possible to verify which conceptions are not possible due to compatibility problems and use this information as guidelines or implementing them in software for the generation of concepts. It is also possible to identify which combinations of solution principles generate conceptions that have the most beneficial relationships, so that when selecting, through comparison, the conceptions that have more beneficial relations increases the probability of generating a design that best meets the requirements.

However, it is not always possible to carry out an analysis of all possible concepts, due to the large number of combinations that makes it prohibitive. For these cases, the use of the relationship matrix in assisting decisions is useful in identifying which elementary functions are most important in the decision-making process. The number of restriction and obligation relations of an elementary function indicates how much this function dictates the particularities of the conceptions. Using the same logic, the number of beneficial relations that the elementary function presents indicates how much the process of selecting the solution principle of this elementary function influences the cost-benefit of the design.

4. CASE STUDY

For the case study, an autonomous robotic platform was used. As a result of an innovative collaboration involving Centrais Elétricas de Santa Catarina S.A (CELESC) and the Laboratories of Applied Robotics (LAR) and Hydraulic and Pneumatic Systems (LASHIP) of the Federal University of Santa Catarina (UFSC). Developed according to the PRODIP methodology according to Back *et al.* (2008), during the conceptual phase of the project the global function was decomposed into 54 elementary functions. Distributed between the elementary functions, more than 300 solution principles were identified, and the achieved Morphological Matrix presented a combinatorial explosion, resulting in

approximately 1.58×10^{24} possible conceptions and in a difficult design task, considering the excessive number of combinations limits the technical and economic evaluation of all of them.

In this case, the Relationship Matrix was used to decrease the number of conceptions and at the same time select which elementary functions are most impactful in the design of the autonomous robotic platform for subsequent analysis.

Manually the group analyzed the type of relationship between each solution principle and selected one of the standardized symbols, its result was added in a spreadsheet created in the software Excel®, subsequently for data processing and graphic creation was used the software MATLAB®. By showcasing the matrix in a spreadsheet, it was possible to quickly verify whether the combination of solution principles is logically compatible, and was also identify which elementary functions are most important for the design creation process through the number of relationships.

For better visualization of the Relationship Matrix, the Kassebaum (2021) circular relationship graph was used. By consulting the graph, it is possible to visualize which elementary functions has the greatest impact on design. Through connecting arcs between two elementary functions, the circular graph represents the presence of a type of relationship and the thickness of this arc qualitatively indicates the amount of this relationship between the two elementary functions. Only the mentioned elementary functions names will be exposed, however, the connecting arcs proportionally represent the actual relationships obtained through the analysis of each solution principle.

Figure 6 shows the impact that each elementary function exerts on the others in the creation of a design for the product. The arc, in this case, indicates that the choice of a certain solution principle of an elementary function will require the choice of another solution principle of the related elementary function.

Figure 6 is, therefore, an obligation relationship graph. It is possible to visualize, for example, that the elementary function “Support the Components (*F14*)” plays an important role in deciding the type of design since it contains several relationships of obligation with other elementary functions, as well as a strong relation of obligation in the decision of the principles of solution of the elementary function “Keep Balance (*F13*)”, with 8 obligation relationships.

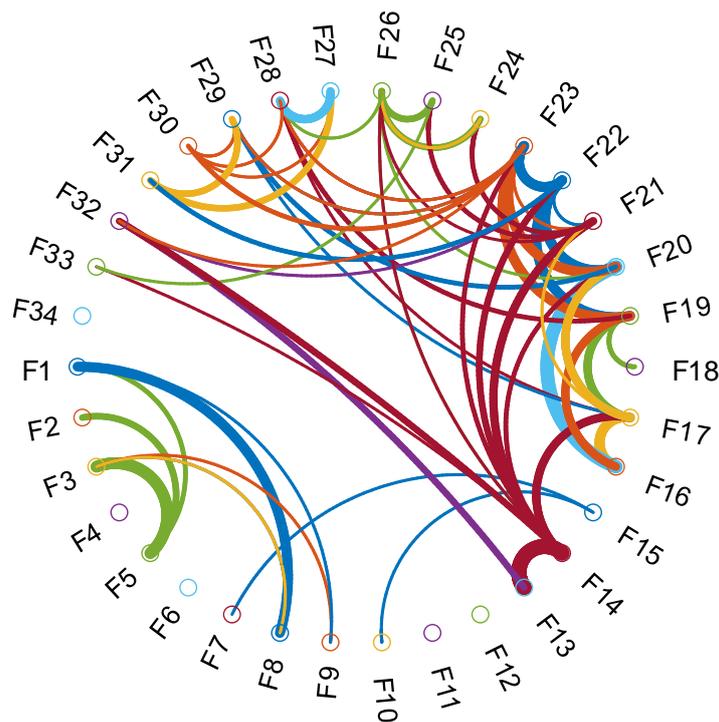


Figure 6 - Morphological Matrix Obligation Relations

Complementary to the analysis of relationships, Figure 7 compares which elementary functions have choices that most benefit the creation of a conception. It is then noticeable, for example, that the elementary functions “Store Energy I (*F1*)” and “Control the Movement (*F5*)” are important to decide which of the possible conceptions presents the best cost/benefit relation, since they have a total of 91 and 101 benefit relationships, respectively.

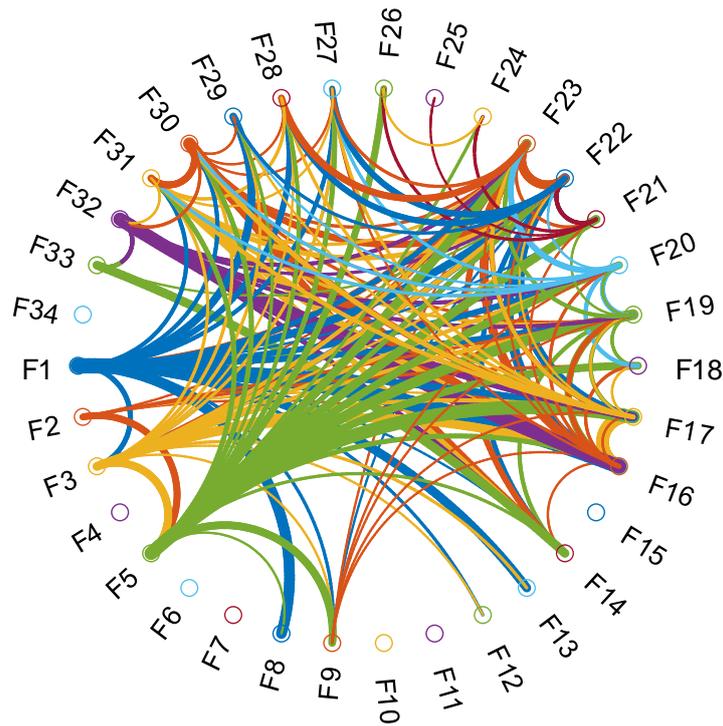


Figure 7 - Morphological Matrix Benefit Relations

In Figure 8 the restriction relationships of elementary functions are represented. It shows that there is a reasonable number of logically incompatible conceptions. Figure 8 highlights the importance of choosing the solution principle of the elementary function “Guides the System (F22)”, for it restricts the creation of a series of conceptions, by having a strong constraint relationship with elementary functions “Recharge Energy (F16)”, with 26 restrictive relationships and a moderate constraint relationship with elementary functions “Store energy II (F17)”, “Transform Energy (F19)”, “Transmit Energy (F20)” and “Moving the System (F23)”, with 16,19,15 and 19 restriction relationships, respectively.

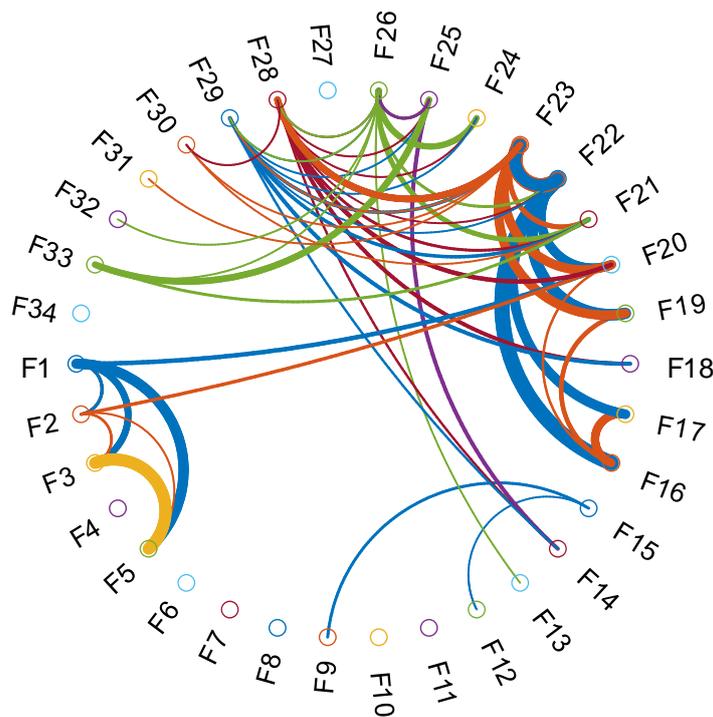


Figure 8 - Morphological Matrix Restraint Relations

5. RESULTS AND DISCUSSION

In this article, a relationship analysis of the principles of the autonomous robotic platform solution was performed. As a result, the Relationship Matrix provided a reduction in the number of combinations for the design creation. At the end of the analysis, 394 restraint relations, 165 obligation relations and 626 benefit relations were selected, and the addition of this information to an electronic spreadsheet allowed a quick procedure of verification of incompatible conceptions for the creative team.

The relationship analysis also supported the choice of the critical elementary functions for the technical and economic evaluation of possible concepts, since the four most important ones were identified through the Relationship Matrix. Conforming to the results, the “Supporting the Components (F14)” with 24 obligation relations and “Guiding the System (F22)” with 95 restraint relations are more responsible for determining the characteristics of the autonomous robotic platform, because it is the functions that limit the process of choosing projects. The elementary functions “Store Energy I (F1)” and “Control the Movement (F5)”, with respectively 91 and 101 benefit relations, were identified as being the most responsible for attributing cost-benefit relations to the autonomous robotic platform. Therefore, greater attention of the project team in choosing the solution principles related to these functions can positively influence the chances that the chosen design will be the one that best meets the design requirements.

Thus, through the case study, the method proposed in the design process was validated. With the use of the Relationship Matrix, it was possible to document the technology compatibility experiences of the project team and decrease the design creation time by providing a quick verification method. It also provided the team the knowledge of which decisions are important when creating a conception, improving the creative process.

6. ACKNOWLEDGEMENTS

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