

COB-2023-1834

CONCEPTUAL DESIGN OF A PLATFORM FOR TRANSFORMER TRANSPORTATION IN DIFFIULT ACCESS LOCATIONS

Lucas Jun Imanisi

Alinne Geronimo

Rodrigo de Souza Vieira

Federal University of Santa Catarina

lucas.jun.i@grad.ufsc.br

alinne.geronimo@posgrad.ufsc.br

Rodrigo.vieira@ufsc.br

Roberto Kinceler

Sidnei Avelino da Silva Junior

Celesc S.A.

rkincelar@celesc.com.br

sidneiasj@celesc.com.br

Abstract. *In residential condominiums, transporting sheltered power transformers can be challenging without access for cranes near electrical substations. Celesc and UFSC's LAR initiated an RDI project to create a robotic, self-propelled platform for efficient transportation of power transformers in difficult access sites. The platform aims to optimize movement within substations and confined areas, overcoming various obstacles along the route. Lack of standardization in transformer dimensions is a major challenge addressed by the project. The Conceptual Design, developed using PRODIP methodology and support tools like Morphological Matrix, Pugh Matrix, and SWOT Matrix, promotes innovative solutions, ensuring safety and added value to the final product. This initiative fosters innovation in the field, delivering safer operations during power transformer transport.*

Keywords: *project methodology, conceptual design, user requirements, maintenance of substations, locomotion of transformers*

1. INTRODUCTION

Many buildings, both residential and commercial, have their own power transformer housed in power transformer substations that are located within the building enclosures. The transformer must be inspected and maintained periodically to ensure that it is working properly, thus avoiding the interruption of the power supply or the occurrence of electrical accidents.

Centrais Elétricas de Santa Catarina S.A, Celesc, when responsible for the proper functioning of the transformer that is housed in substations and if there is a need for its replacement, it needs to mobilize a team to carry out the task of moving the transformer safely from inside the substation to outside the condominium premises or vice versa.

The team's task is extremely complex, as building transformers are often large and heavy, not to mention the problem of the limited space of both the substation and the path to be traveled, which may contain narrow corridors, small doors, ramps, steps, bumps and grills, which often makes it impossible to use a large machinery to load the transformer. In this way, human labor remains, which is not as efficient or as safe to perform this task and can take hours to be performed in addition to generating a great risk to employees.

Considering the problems involved in this operation, Celesc together with the Raul Guenther Applied Robotics Laboratory (LAR), started the project to develop a robotized, reconfigurable, and self-propelled platform for the transport of transformers in places of difficult access. This work aims to present the development of the Conceptual Design of the platform, elaborated through the model of industrial product development processes - PRODIP, developed by the Center for Integrated Product Development (Nedip) (BACK, OGLIARI, DIAS & SILVA, 2008).

During the Conceptual Design, achieving the best solution that meets the design specifications and the client's wishes is the main goal. To this end, different solutions are generated and analyzed by the team, aiming to meet all requirements and add value to the product. One of the main focuses in the development of the concepts developed in the project under study was the ability to work in places of limited space, overcome obstacles and be able to transport oil and dry transformers that are in the power range of up to 300 kVA and 500 kVA, respectively.

2. CONCEPTUAL DESIGN

The use of design methodologies and the use of support tools, facilitate the development of the project and the evolution of information that start as qualitative and develop to quantitative and detailed (ROMANO, 2003).

For the development of the robotic, reconfigurable, and self-propelled platform for the transportation of transformers in places of difficult access, the methodology of industrial product development process - PRODIP was used, which is described by BACK, OGLIARI, DIAS & SILVA (2008). This methodology is separated into three major steps, namely: planning, design and implementation, which are in turn subdivided into sub-steps. This article deals with the Conceptual Design stage which is a subdivision of the design stage. We can see the schematic model of the PRODIP Methodology in Figure 1.

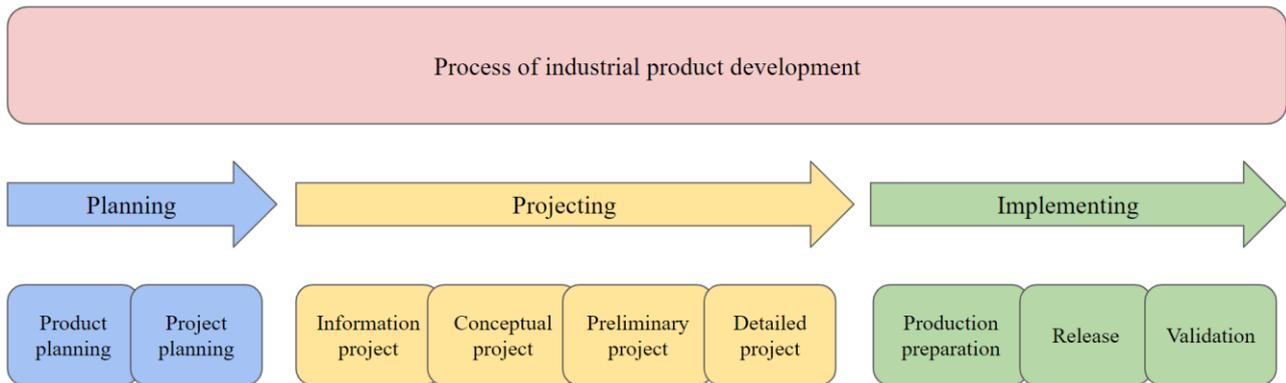


Figure 1 - PRODIP Methodology (adapted from ROMANO, 2003)

2.1 Function structure

In the Conceptual Design, the solution principles are determined that together meet the project objectives. According to PAHL & BEITZ (1998), to achieve such results, it is necessary to establish the functional structure of the product by analyzing the essential problems and challenges, finding their respective solution principles and combining these principles in a functional way.

The functional structure of a product describes the various functions performed by the product at different levels of complexity, starting from the most complex function and dividing it into simpler functions (PAHL & BEITZ, 1996). The functional structure adopted in the project is composed of three levels (Figure 2), being the highest level in the abstraction called "Global Function", which describes the general function of the product, determined from the analysis of the project requirements. The second level, called "Partial Functions", aims to further specify the overall function by breaking it down into clearer sub- functions indicating how the product will accomplish the overall function. The third level simplifies the partial functions by creating a new set of sub-functions for each Partial Function, which are called "Elementary Functions", presenting simple solution principles.

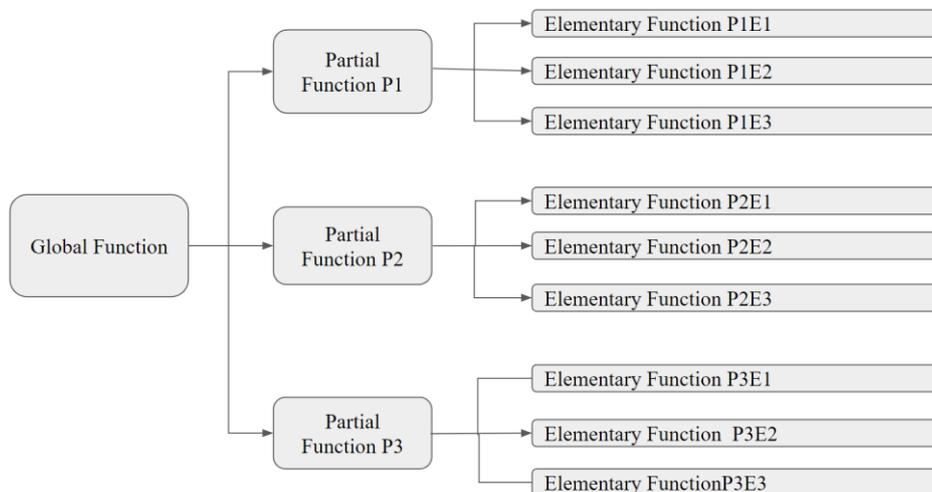


Figure 2 - Breakdown of the total function into simpler functions.

Thus, the Conceptual Design Stage was initiated by establishing the function structure. To this end, the global function was defined as transporting transformers in residential condominiums, since, in line with the project objective, the platform must transport transformers from the curb to the condominium substation and vice versa.

The partial functions come from the unfolding of the global function, such as: moving the platform, moving the transformer, controlling the operation, ensuring safety, among others. The elementary functions that come from each partial function are numerous, reaching a total of 54. These functions are related to each other and some have a greater degree of impact on design decisions than others. An example of the beginning of the unfolding of the project functions can be seen in Figure 3 but, in order to make the article more objective, these will not be discussed.

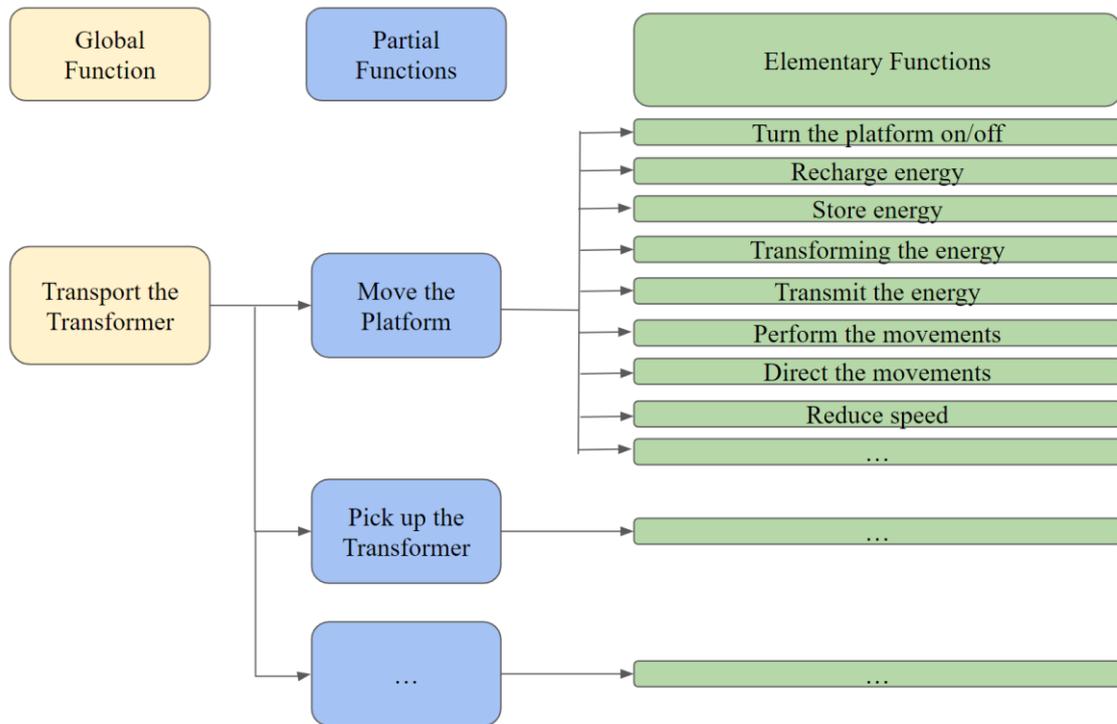


Figure 3 - Example of a functional structure with the breakdown of functions.

After the unfolding of the elementary functions, several solution principles are proposed for each elementary function, making it possible to generate various product designs through the different combinations of solution principles.

2.2 Morphological matrix

With the structure of functions established, we move on to the stage of determining the possible solution principles for each elementary function, thus being a stage that involves a lot of creativity. In a complex project, which involves a greater number of elementary functions and solution principles, it is important to use support tools so that the team is assertive and efficient when generating the designs for the product. In this way, a creativity method was applied.

The choice of the creative method depends on many factors, such as individual aspects of each team member, the creative potential and characteristics of the work team, the project objectives, the application area (more technical systems), among others. It is extremely important to know the different creative methods to make the most appropriate choice (BACK, OGLIARI, DIAS & SILVA, 2008).

As it is a well-structured method and the project is a complex problem, the team chose to use the Morphological Matrix (MM) method, as it allows the division of the general problem into simpler problems.

The Morphological Matrix consists in generating conceptions by combining the solution principles of the different elementary product functions, as shown in Figure 4.

In the MM, the information is distributed neatly in columns and rows. The second column is for the distribution of the elementary functions while the other columns show the solution principles, as shown in Figure 4. Thus, each row shows the solution principles found for a given elementary function.

Partial Functions	Elementary Functions	Solution principles					
Move the Platform	Interrupt/maintain power to the platform movement system	Clutch + brake system	Valve				
	Recharge energy	Storage tank	Combustion emergency system	Energy recharge by vibration of the system	Regenerative brake system	Battery charger	Extra battery
	Store the energy	Fuel tank	Batteries	Hydraulic accumulator	Compressed air tank	Supercapacitor	Flywheel
	Transmit the energy	Classic mechanical transmission	Electric transmission	Hydraulic transmission	Pneumatic transmission		
	Execute the movement	Wheels + axle	Treadmill	Legs	Omnidirectional wheels	Pneumatic system that propels the platform by rails	
	Transform energy	Combustion engine	Electrical systems (generator/alternators, connectors and actuators)	Hydraulic assembly (pumps, connections, actuators)	Pneumatic assembly (compressor, valves, hoses and actuators)		
	Transmit the energy	Classic mechanical transmission	Electric transmission	Hydraulic transmission	Pneumatic transmission		
	Directing the platform	Mechanical / assisted steering	System of independent differentials	Chassis with omnidirectional wheels	Electric power steering	Linear actuator	Electric actuated suspension

Figure 4 - Example of choice of solution principles in the Morphological Matrix

2.3 Generating product design

From the data collected from the Morphological Matrix, the generation of possible product designs is started, which will later be evaluated through the Pugh Matrix, which will be discussed below.

From this stage of the process, the team had two initial objectives: prioritization of functions and relationship of solutions. The prioritization of functions focused on defining the minimum number of elementary functions capable of generating the first physical design of the product, focusing on the functions that present solutions with the greatest impact conceptual in solving the overall function of the project (STEIN, GERONIMO, ALVES, VIEIRA, KINCELER & JUNIOR, 2021).

These analyses were necessary due to the excessive number of combinations between the possible solutions found for each elementary function present in the Morphological Matrix. To minimize the problem of combinatorial explosion among the possible solutions, and optimize the innovation process, the team developed a new tool entitled Lean Morphological Matrix (LMM). The application of the MME resulted in a set of elementary functions called protagonists, which were used during the generation of the initial product designs. The process of developing and applying the MME is presented and discussed by STEIN, GERONIMO, ALVES, VIEIRA, KINCELER & JUNIOR (2021).

The relationship of the solutions aimed to study and define how the elementary functions were related, analyzing the degree of impact of the choice of each solution principle on the project as a whole, studying how the choice of a solution principle restricted or forced the choice of other principles related to other elementary functions in the MM. This analysis was developed from the perspective of how the choice of a solution principle interferes, forces or prevents the choice of the rest of the set of principles. Thus, by studying the elementary functions of the Morphological Matrix and verifying the relationships between the solution principles, the decisions that have the greatest impact on the concept creation process were identified, aiming to improve the creative process and reducing the number of possible combinations (CARVALHO, CAVALLI, VICTORETTE, VIEIRA, KINCELER & JUNIOR, 2021).

Achieving the initial objectives, which resulted in the Lean Morphological Matrix and the relationships and impact analysis of the sets of solution principles of each elementary function, the initial product conceptions were generated.

From this moment on, the team aimed to generate as many conceptions as possible, joining similar conceptions, improving and developing different proposals, aiming at innovation and the potential of each concept (for reasons of contractual project confidentiality, the conceptions generated will not be exposed in this article).

To evaluate the designs, the Pugh Matrix was used, allowing the evaluation of the designs according to criteria defined by the project team. An example is shown in Table 1, where the designs are evaluated according to the chosen criteria, which are the user requirements established in the initial stages of the project, each containing a specific weight. The design with the highest final score is the one that best meets the set of criteria and is therefore chosen to be further developed in the next stages of the project.

Table 1 - Example of the Pugh Matrix (based on BRITO, 2020)

Criteria	Concepts				
	Conc. REF	Conc. A	Conc. B	Conc. C	Conc. D
Overcoming obstacles	0	+	-	+	-
Adapt to the load		0	-	0	+
Be compact		+	0	+	+
Have good maneuverability		0	+	0	-
Immobilize the load		0	-	0	+
...		-	0	+	+
Sum of more (+)	0	2	1	3	4
Sum of minus (-)	0	1	3	0	2
Sum of zero (0)	6	3	2	3	0
Final Results	0	1	-2	3	2

Initially, a total of 24 user requirements were used as a parameter to evaluate the 14 product designs generated, among these requirements are: transposition of different obstacles (steps, doors, ramps, among others), adapt to the load, be compact, have good maneuverability, ensure the immobility of the load, among others. This initial analysis resulted in five best-placed designs (which had very close scores). From this impasse, the team refined the proposals of the five designs, so that they could be re-analyzed by the Pugh Matrix. Once the user requirements had already been met, the evaluation criteria of the Pugh Matrix were reformulated, thus the five designs were evaluated according to their potential in different aspects, such as: transporting the stipulated transformer family, level of innovation, transposing doors, loading and unloading the transformer inside the substation, the complexity of the proposal and operation, among others.

2.4 Final conception

After the evaluation of the five conceptions from the Pugh Matrix, the conception that best met the requirements established by the team was called Conception C7, represented in Figure 6.

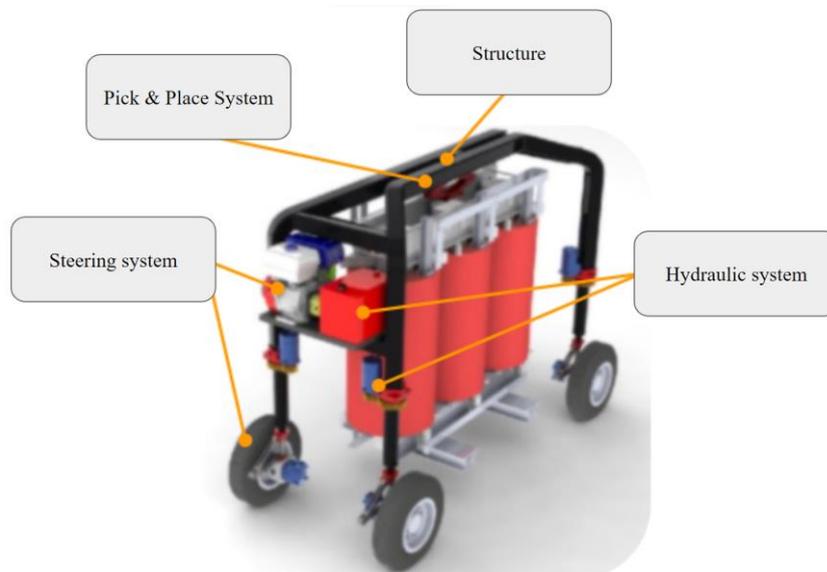


Figure 6 - Design C7

Design C7 was developed to achieve the best framework in relation to the cost- power ratio, as well as to meet the other demands and needs of the project. With a simple tubular structure, good utilization of the transformer space, potential to overcome all the proposed obstacles and a large portfolio of possibilities for the platform subsystems, the C7 is a design with the potential to be efficient, compact, simple and viable.

This design was elaborated with the size of the access doors to the transformer in mind, which were one of the main obstacles observed during the early stages of the project. To this end, its wheels are able to rotate on their own axis, allowing passage through narrow passages.

The Pick & Place system, which has the role of picking up and lifting the transformer, is formed by the whole design, both the vehicle structure and the mechanism chosen to pick up the transformer, in this case, a mechanism inspired by a scissor jack, illustrated in Figure 6.

The platform's propulsion system consists of a diesel engine connected to a hydraulic pump and hydraulic motors in the steering system. In addition, the hydraulic system relies on linear actuators in the suspension to level the platform in any operating condition, maintaining the stability of the system.

The steering mechanism consists of a simple gear train coupled to a hydraulic motor at each wheel, acting directly on the linear guide of the suspension. The suspension mechanism, independent for each wheel, resembles the airplane nose mechanism, found, as the name suggests, in aeronautical applications, relying on a hydraulic piston, acting as an active actuator of the suspension for the leveling of the platform in any runway condition.

In order to reconfigure the platform and improve its stability, the design includes a gauge variation mechanism. This increases the stability polygon, allowing the range of larger transformers to be transported without the risk of tipping over.

To enhance the analysis of the design potential, Design C7 was virtually tested in SolidWorks (2017) against the main obstacles encountered in the design routes, which are simple ramp (Figure 8 a), curved ramp (Figure 8 b), steps (Figure 8 c), doors and substations (Figure 9).

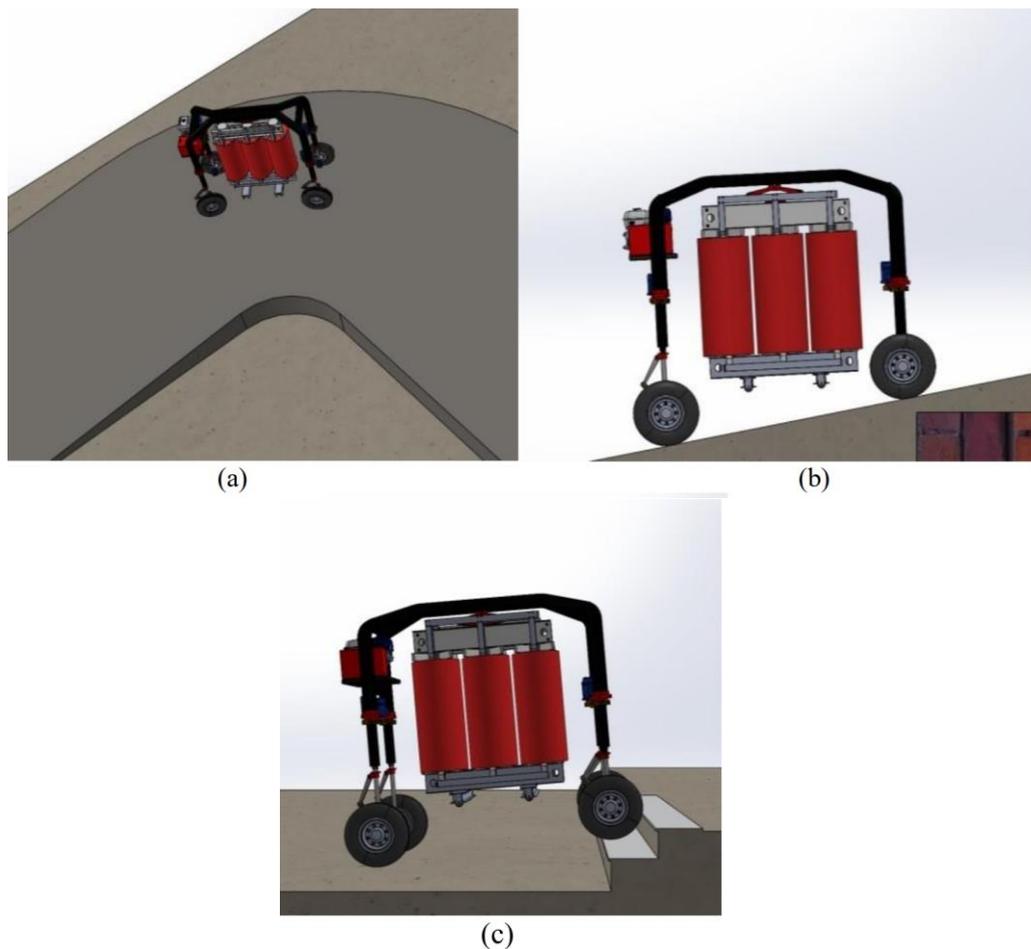


Figure 8 - Simulation of the platform traversing (a) simple ramp with 20% inclination, (b) ramp with curves, (c) steps.

The design showed great potential in the tests performed, as when subjected to uneven ground, the platform adjusts the suspension keeping the transformer level, resulting in no or very low tipping moment. Design C7 also did not present

difficulties to enter and pick up the transformer in substations during the virtual tests (Figure 9). Since the independent movement of its wheels allows a good maneuverability even when in confined places.

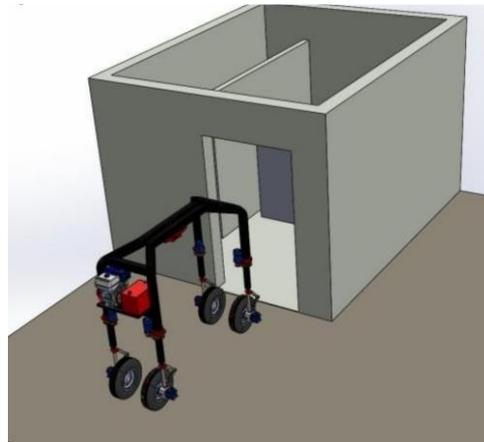


Figure 9 - Virtual test in simulated substation.

For a clearer and more direct visualization of the C7 design, a SWOT Matrix was drawn, which comes from the English terms, Strengths, Weakness, Opportunities and Threats, represented in Table 2.

Table 2 - SWOT matrix of design C7.

Forces	Weakness
- Compact	- Complex control due to the number of actuators
- Lightweight	
- Small radius of curvature	
- Good control of CG position	
- Reconfigurable	
- Low cost	
- Simple mechanism	
- Ease of overcoming obstacles	
- Zero overturning moment	
- Low height	
Opportunities	Threats
- Control of the steering system	- Old condominiums with unforeseen obstacles
- Leveling control	- Non-standard transformers
- High degree of innovation	

3. CONCLUSIONS

During the Conceptual Design, the team had two major phases, the definition of the protagonist functions and the generation and definition of the product design from these functions. These two major phases may seem elementary, but in a large project, the development is somewhat complex due to too much information to be analyzed. In this regard, the PRODIP methodology, the use of tools such as the Morphological Matrix, the Pugh Matrix, the development of the Lean Morphological Matrix and the impact analysis of the choice of solution principles were essential.

The transformer transportation platform project is still in progress, but the team can already notice the benefits of using the methodology, being able to deliver the product concept within the pre-established deadline in the project scope, achieving a result considered positive, since the concept delivers all the requirements and brings innovation, adding value to the product.

In the next stage of the Conceptual Design, the Preliminary Design, the team could notice that some specific points of the chosen design should be re-evaluated according to a technical feasibility analysis, an example is the Pick & Place system, which, due to the variation of the dimensions of the grip points in different transformers and the limitation of the available space, pointed out the unfeasibility of a mechanism similar to the scissor jack, so it was necessary to choose another solution principle for this elementary task.

Both the industrial product development process methodology - PRODIP, and the tools used to develop the product concept of this project, were of great importance and presented a positive result in the project, optimizing the time of the tasks, avoiding rework and enabling the search for innovation in the generation of concepts.

Analyzing the design generated, it can be seen that the team was able to identify the biggest challenges for the development of the product, delivering a final concept that meets the design requirements, where the biggest impediments to its development are related to possible obstacles that escape the rules found in standards.

The authors are grateful to Celesc for all the financial support received during the development of the project and to the Research and Technological Development Program of the Electricity Sector regulated by ANEEL. They are also grateful for the support received through LAR and UFSC, for the support and contribution of the entire research and development team and other entities involved. Finally, the authors would like to thank all the members of the team of the Research and Development and Energy Efficiency Division (DVEE) of Celesc Distribuição S.A., in the persons of Mrs. Maria de Lourdes Machado Viccari, and Luiz Afonso Pereira Athayde Filho, for monitoring the administrative and financial execution of the project. In particular, they also thank Engineer Thiago Jeremias, DVEE Manager of the R&D and EE Program of Celesc, for his attention and promptness, which made possible the realization of this project.

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