CONCEPTUAL DESIGN ON DEVELOPMENT OF BAJA'S MECHANICAL TRANSMISSION

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Abstract. *The mechanical transmission design of off-road vehicles, used in academics competitions known as baja, is fundamental in efficiency of potency of vehicle. Since the vehicle must alloy a higher torque variation and velocity compatible with the competition's track obstacles. For this, the objective of this work is develop the conceptual design and embodiment design of a mechanical transmission for a vehicle baja to competitions Baja-SAE. This project has been divided in four design phases: Task Clarifications, Conceptual Design, Embodiment Design and Detail Design. In task clarification, was obtained the requirement list which indicated for design team which the system should be light (weight less then 7 kg), high reliability (more then 90 %) and mainly low power loss (less then 20%). In conceptual project, has been divided the overall function transmit power with maximum efficiency, in two subfunctions: primary reduction (vary the transmission's relation) transmit power to shaft and secondary reduction (final drive ratio). These subfunctions represent in this project the mechanical transmission. For each one, has been given forms to individual solution, and in the end, have been mounted principle solutions variants with combinations between these solutions. For finalize the conceptual phase, has been elaborated a objective tree of classification for these solutions variants. In this tree, has been set securities parameters, manufacture and technical reasonable to baja's mechanical system, being defined weights for each criterion, according to the degree of importance. The choice of solutions variants has been realized in a reunion with the project team, which assigned notes according the guideline VDI 2225 (score 1 to 5, with 1 being unsatisfactory and 5 being very good) in evaluation's criteria (operational safety, security of operator, system reliability, easy operation, low power loss, easy maintenance, manufacturing in a short time and reduced manufacture cost). After, has been multiplied the weights of each item by the variant's score, being added the obtained values. So the variant with highest score has been the solution with CVT (continuously variable transmission) as primary reduction, spline shaft, a ratio with chain drive for secondary reduction and CV shaft to torque transmission to wheels. In embodiment project, has been used software CAD to draw, simulation and sizing of constituents parts. In the detail design, has been used the draws produced in the embodiment phase to manufacture and purchase the components, that will be implemented in vehicle to test and redesign.*

Keywords*: Machine Design; Mechanical transmission; Baja; Design Methodology*

1. INTRODUCTION

Big projects, when it wishes innovation and acceptability in the consumer market, require the application, with maximum efficiency, for a design methodology. However, if the project team were not interdisciplinary, interactive, and mainly creative, the project chances to be unsuccessful in the market is huge. So, the theoretical and creative foundation, supported by a methodology is fundamental to the project success. (Delgado Neto, 2010).

In 1962, Morris Asimow begin to systematize the methodology, in Introduction to design. After Asimow, several works were based in his ideas, but according to the evolution of the consumer market and the available technologies, with the advent of softwares CAx, that helps and boosts the project steps, another methodology were fundamentals.

The methodologies systematized the project in a way that an abstract idea is formalized in a concept, by the way that every size, specify, and finally fabrication. However, until reach the step that the project team owns the solution principle, is necessary execute the conceptual project, responsible for the abstraction transformation to a concept. When a concept is defined in a stage where the high level of uncertainly still predominant (in a previous stage of conceptual project), the designers tends to elaborate a solution without a well consolidated theoretical foundation. This orientation in the solution will generate unforeseen needs, that can only be found in a next concept (Mendes, 2009)

The conceptual stage consists in a series technical activities implemented in order to develop a new concept (Li et. al., 2010). Besides, it is characterized to the big participation creative intellect of the designer, been considerate the step that detached a higher creative effort (Mendes, 2009). However, with many of ideas, coming by the designers, it be defined by dispersed forms, it needs to be worked in, aiming to better formalize the concept (Almeida, 2000). Pahl et. al. (2007) defines, in a objective way, the conceptual stage with a step that is selected a solution principle. For him, the division of this stage takes the form shown by Fig. 1.

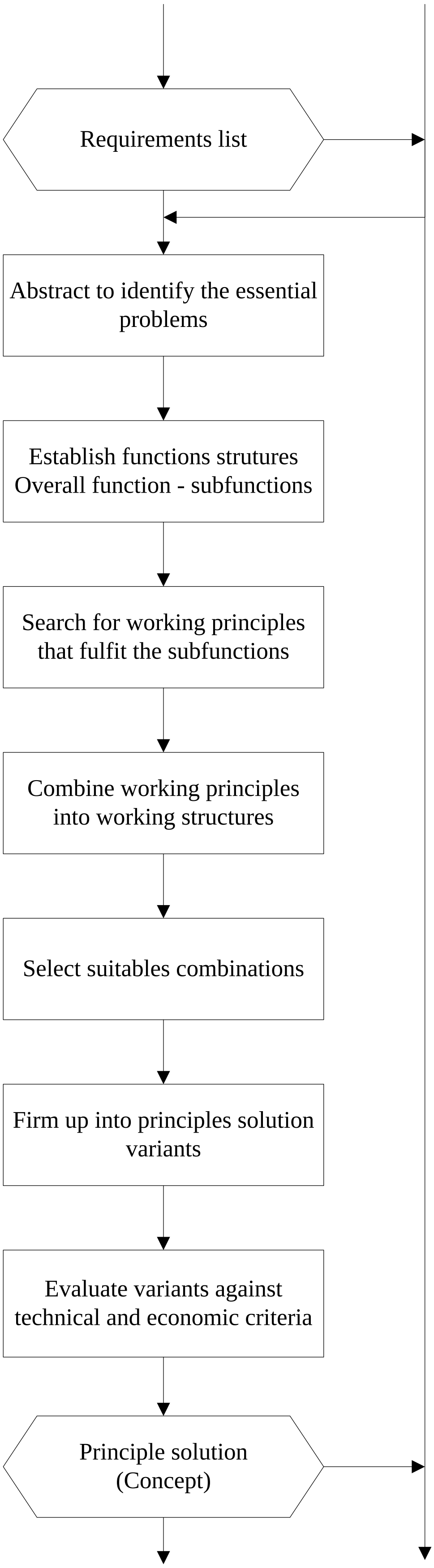

Figure 1 – Division of conceptual project stages (Pahl *et.al.,2005)*

In a mechanical system, when it wishes to obtain several relations between torque and speed, it uses a transmission system. There are several types of transmission such as mechanical, hydraulic and hydro-mechanical. To a vehicular transmission, mechanical transmission is generally used. In this type, is applied different types of machine elements such as gears, pulleys and chains. To select the best alternative, it is analyzed for their economic, powertrain global efficiency, system life and other criteria.

By combining a design methodology to a transmission of a off-road vehicle, the team project plans to get a system in which both interests of the market for the product and technical details, such as high range of variation of torque and speed compatible to the vehicle, are considered. Thus, the need for a systematic design for the generation of a product with a marketing strength is evident.

2. OBJECTIVE

The objective of this work is to develop a conceptual project to a transmission system off a off-road vehicle, to academics competitions, using design methodology.

3. METHODOLOGY

The methodology of a conceptual project were based in projects stages proposed by Pahl et. al. (2007). The conceptual stage were started by specifying of the project, obtained during the informational stage, which were obtained from a range of values that served as reference for the design requirements. As a result, the project consisted in the execution of the first stage known as clarification of the problem, which set up the necessary functions of the machine to reach the goal. At that stage, was not generated any type of solution, but the definition of the basic problems in a generalized way. Through these problems, were started the stage of establishment of functional structures, which first signed a global function. This global function allowed, in form of diagrams, to represent the input and output of material, energy and signal. Through this function and sub-function structures allowed define the necessary sub-functions to reach the global function (motor power transmission to the vehicle rear axle) and the interrelation between both. The next stage of the conceptual stage is was the search of solutions to the sub-functions, been established, with the sub-functions union with their respective solutions to the morphological matrix. In this matrix, in the first column, were described the sub-functions, and for each line, were related the solutions to each sub-function. By this matrix, were made combinations between the compatibles solutions principles, that obtained a set of combinations of principles. These principles (or variants), after being laid, were evaluated according to requirements and design specifications.

To evaluate the combinations in a quantitative way, it was necessary define a criteria tree based in the project requirements and technical criteria, of security and economics with their respective values defined by the team project. The score to evaluation, without considered the defined value in the criteria tree, were based in VDI2225 guideline (Pahl et. al. (2007)), been utilized the minor band, with scores ranging between 1 and 5. Thus variants of solution were scored and classified, and those better classified used for the stage of draft and final analysis of the concept.

4. RESULTS AND DISCUSSION

The Table 1 presents the project specification defined based in the projects requirements. These requirements were part of the definition of the criteria tree used to evaluate the obtained variants of solution

Table 1 – Project Specification

Design Requirements	Design Specification
Low weight	< 7 Kg
High reability	> 90%
Low loss of power	< 20%
Have safety devices	-

It's been defined for each item, a range of benchmarks. This band is used as a started goal, by the team project, to be achieved by the product. However, due to the high degree of abstraction concerning referent of this stage, these values may be inconsistent during the project development, with necessary revisions and updates of both.

4.1. Selection of the global function and the material, energy and signal flow

Continuing the design stages, it was begin the conceptual stage. First, we defined a global function, but also the low of incoming and outgoing material, energy and signal. For the transmission system of the vehicle, is must be given torque and speed (power), effectively, when which are most needed – as, for example, high torque to climb hills and high speed in straights. Besides enabling the combination of both (torque and speed), in cases where it is needed. Soon, it became evident that is was regarded as a function of the overall system to transmit power to the wheels, we would be representing in general, the objective of the transmission system.

In relation of the material, energy and signal flow, as it is a off-road vehicle, it appears that, for material, the entry would be the lubricant necessary for the functioning of the system in good condition, beyond impurities, because of the track conditions in which it is submitted that type of vehicle. Impurities were also included in the output of material, because of periodic maintenance that will be realized to ensure a properly functioning system. On energy , the entry would be mechanical energy from the engine, which is the only energy source allowed for the Baja vehicle.

As is known, in the transmission elements occur energy losses, reducing the net power to the wheel, the magnitude of these losses were evaluated on the structure and function of dissipated energy for the signal, the system requires no signal for its operation, then the entry was considered null. However, the transmission system can provide important data, such as rotation speed and for the telemetric system and for the pilot. Therefore they considered as output signals. Given all these considerations, the team project completed the initial part of step with the conceptual scheme shown in Fig. 2.

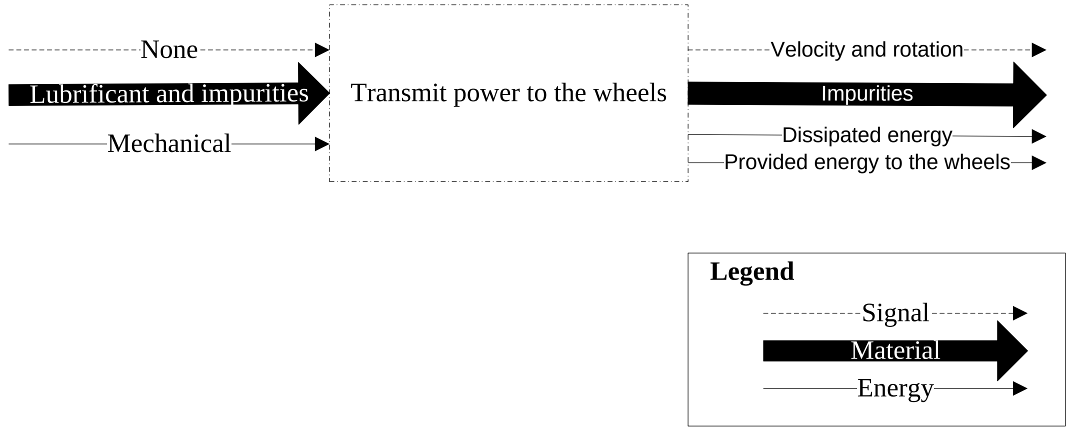

Figure 2 – Global function and material, energy and signal flow

4.2. Division of the global function in sub-functions

After the definition of the global function, the project team noted that this function should be slit due to their high degree of complexity. Therefore, it would require the division of the global function in sub-functions that obtain better visualization and solution. Thus, the global function of transmitting power to the wheels was subdivided into two fundamentally subfunctions, called reduction of rotation and transmit torque. As this type of vehicle should be worth more than one gear ratio due to the high speed provided by motor (maximum speed of 3800 rpm), the subfunction reduction was divided into two other sub-functions: primary reduction and secondary reduction. Therefore, it became possible to carry out the change of global function by subfunctions. In the scheme presented in Fig. 3, was represented in more detail the material, energy and signal flow.

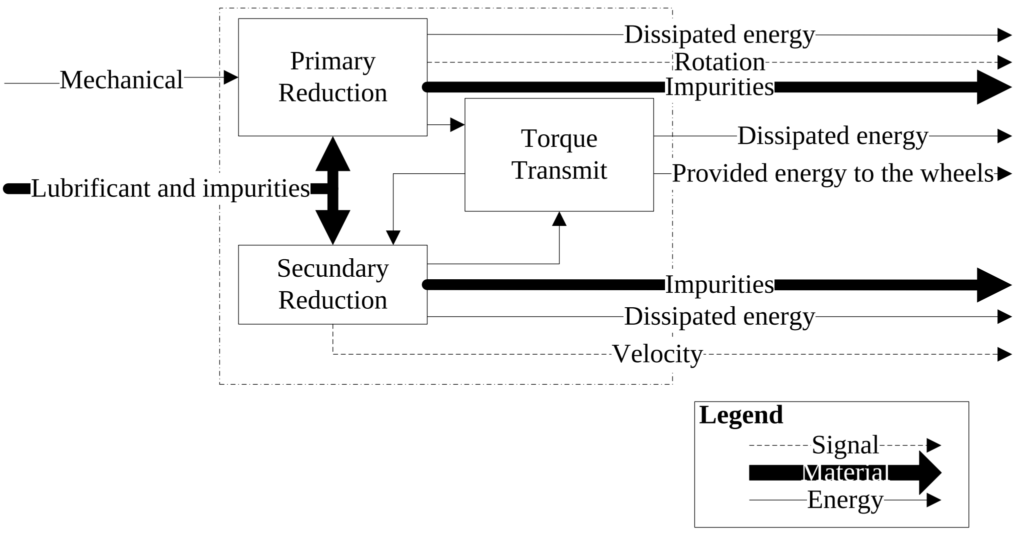

Figure 3 – Subfunctions and material, energy and signal flow detailed.

When idealized transmitting torque as a subfunction aimed to cover most types of axis. For the input torque to the primary reduction, we used the motor shaft itself. Impurities come mainly in two reductions being required do develop the project, the idealization of safeguards to minimize the entry of the same. The energy dissipation occurs mainly in the reductions, but there will also be dissipated in the axes, through the couplings. The rotation is set through the fixture attached to the motor shaft, as it still has not been applied any gear. The speed is found by combining the output speed (the wheel) and the effective radius of scroll (found by analyzing the tire).

4.3. Morphological matrix

Through bibliographic research previously performed to the execution of the conceptual stage, were found for each subfunction various forms of solution. Therefore, with the combination of these solutions and their subfunctions we have the construction of the morphological matrix. The principles of a solution for primary reduction and secondary reduction are similar, but some were not used in the two subfunctions. For reducing primary solutions, three alternatives were found, which were: CVT (Continuously Variable Transmission), gearbox with cylindrical gear with straight teeth and gear box with cylindrical gear with helical teeth. All of them allow change the transmission ratio, and the CVT provides an infinite number of relations (between the minimum and maximum), while gearboxes provides a finite amount of relations. As the CVT works with a fixed rotation of the engine, if it is regulated to the rotation of the engine provides more torque, we will have a maximum yield supplied by the engine. In addition, CVT is an automatic transmission, so it is unnecessary the pilot concern to find the best value during the endurance race. Since the gearboxes require the selection of the pilot to a optimum ratio to the situation founded on the track, but provides high performance in the gears. Therefore, the CVT gearboxes were considered as good solutions for reducing primary.

To the secondary reduction, only the solutions of the reduction gear boxes used were primary. The other reductions were selected for this subfunction: belt, sprocket, chain, gear with straight teeth (single relation), cylindrical gear with helical teeth (single relation) and differential system. Because all of these solutions allow only one transmission ratio, in most of the cases, the variation of the reduction will only occur the primary reduction.

The solutions founded transmit torque subfunction were determined through the manufacturing process, elements in which they are attached, and the degree of freedom that it allows, they are: striated /keyed axle, keyed/keyed axle, driving shafts and axles with homocinetics. Many options for the subfunctions have not been used in the composition of the morphological matrix because they are not applicable due to technical and economic issues, the type of vehicle for which that system is being developed. At the end of this sub-step, the morphological matrix was developed, shown in Fig. 4.

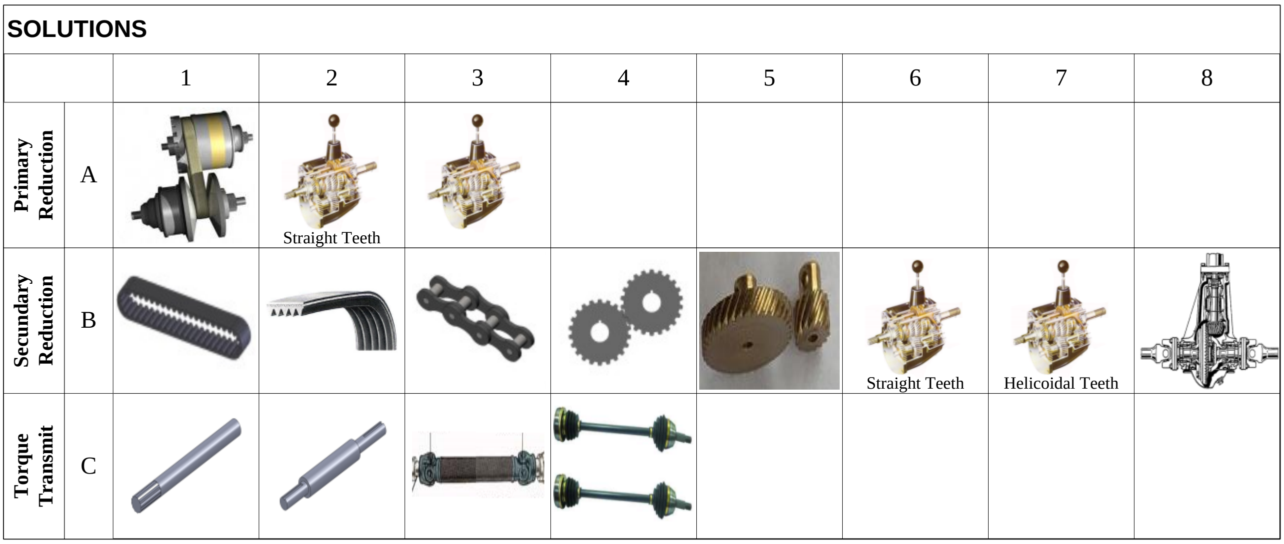

Figure 4 – Morphological matrix for the transmission system

4.4. Variants formulation

Through morphological matrix, it has been possible elaborate fourteen variants, which represent potential solutions to the transmission system.

In the variants elaboration, certain criteria were adopted. First, were observed solutions for each subfunction, therefore some combinations were eliminated, like for example, a variant with gearbox with primary reduction and secondary reduction. Beyond that, there was the torque transmission subfunction (before the torque reach the wheels) in which the transmission and suspension should be considered for its definition. Since the work is directed only to transmission, the axles with homocinetics was utilized to all variants, because in the step that it is recommended (the suspension project) was already finished.

As the project should be as comprehensive as possible, projects have been developed since the simplest to most complex projects. It went through a pre-assessment, through technical parameters and production, following only the variants that possessed a condition to be uses in Baja vehicle. In Table 2, the fourteen variants produced are shown.

Table 2 – Solution Variants

Variant	Technical Specification
1	CVT, striated-keyed axle, cylindrical gear with straight teeth, axles with homocinetics.
2	CVT, striated and keyed axle, cylindrical gear with helical teeth, axles with homocinetics
3	Gearbox – Straight teeth, keyed-keyed axle, cylindrical gear with straight teeth, axles with homocinetics.
4	Gearbox – helical teeth, keyed-keyed axle, cylindrical gear with straight teeth, axles with homocinetics.
5	CVT, striated-keyed axle, Gearbox – Straight teeth, axles with homocinetics.
6	CVT, striated-keyed axle, Gearbox – helical teeth, axles with homocinetics.
7	CVT, driving shaft, differential, axles with homocinetics.
8	CVT, striated-keyed axle, chain, axles with homocinetics.
9	Gearbox – Straight teeth, keyed-keyed axle, chain, axles with homocinetics.
10	Gearbox – helical teeth, keyed-keyed axle, chain, axles with homocinetics.
11	Gearbox – Straight teeth, keyed-keyed axle, toothed belt, axles with homocinetics.
12	Gearbox – helical teeth, keyed-keyed axle, toothed belt, axles with homocinetics.
13	CVT, striated-keyed axle, toothed belt, axles with homocinetics.
14	CVT, striated-keyed axle, belt, axles with homocinetics.

4.5. Criteria tree elaboration

Variants analysis was performed according to safety, technical, maintenance and production requirements. The concept design in the end it should be safe such for pilot as for the people around the vehicle. In addition, the system should be easily maintained and easy mounting. Like most teams, the car is designed and assembled in short periods of time, this criterion also had to be adopted as well as analysis parameter for the variants.

Therefore, it was determined that an efficient transmission system for all criteria presented would be the concept to be developed, thus being considered the general criterion. This item, in a later level, was divided into four questions, which are: Safety Specifications, Maintenance and Production, being the weight respectively 30%, 50%, 10% and 10%, totalizing 100% of the general criterion. This weight distribution takes into account the requirements of the customer, who wished to end the informational design a car that has technical features predominate.

To finish the construction of the tree, the four criteria were broken down in categories in which evaluations were made. In Figure 5, we present the analysis criteria with their weights.

Figure 5 – Criteria tree

4.6. Variants evaluation

After the criteria tree finalization, the project team performed a preliminary analysis of the variants in order to define what would be most interesting to be analyzes and thus select the concept. Initially, two variants have been discarded, because the relevant technical details. The first one was the variant 7, which has a differential system with a very complexity design, high weight, in addition to the system is not widespread among the other competing teams. Another variant that was excluded was the number 14, which has a secondary reduction belt. This variant was excluded because the minimum wheelbase necessary for this type of transmission is recommended a wheelbase of at least one time the pulley with largest diameter (Shigley (2005)). Commercially, the smaller pulley founded was with 75 mm in diameter. Considering a reduction of 6(reasonable value for the secondary reduction) will have a minimum distance between axis is 450 mm. Therefore, this type of transmission proves impossible to implement in this type of vehicle.

After excluding the variables that did not attended the specifications, an analysis was made of the remaining variants through the criteria tree being discussed item by item in order to score each variant. Such analysis was not considered final, since that the intention is to select the three best scored variants for a more careful evaluation.

In relation of operational safety, which is evaluated the safety of everyone around the vehicle, excluding the pilot, all variants except the 8, 9 and 10 variants, were considered good, receiving score 4. The 8, 9 and 10 were considered tolerable, receiving, therefore, score 2, because of the risks offered to release the chain, with a possibility to strike anyone. If any of these three variants, previously mentioned, is the concept variant, should be designed, mandatory, a guard for the chain, with the objective to ensure safety for everyone around the vehicle.

When analyzing the safety of the operator, all variants were considered good (score 4), since the pilot is already safe in relation to the transmission system due the security members, as the firewall, required on this type of vehicle. This wall, according to Baja SAE Brazil Regulation (2011), should be made in metal, at least 0.508mm of thickness and located between the cockpit and the engine compartment, also where is located the transmission system.

For the reliability of the system, came to the conclusion that simples systems would be more reliable due to less design, manufacture and maintenance complexity. Thus, more complex and elaborate designs (such as gearbox with helical teeth) received the lowest ratings and simples design (as chain) received top marks.

Analyzing technical specifications, in the issue of easy operation, variants that the pilot needed to perform any movement in relation of the transmission system to guide the vehicle was considered as very good and received scores of 5. Systems which needed, in part, the intervention of the pilot (CVT associated with one type of gearbox, for example) were considered good, scoring 4. Since the variants that the change of ratio depends only of the pilot (as a variant which the primary reduction is realized by a gearbox), were considered appropriate, scoring 3.

Even in technical specifications, in the issue of low power losses observed that variants with flexible transmission on elements such as belts would have, among the principles of solution, a higher loss of power, resulting from the friction generated between the belt and pulleys. Regarding the toothed belt, we do not have the same problem, since that the transmission made by this type of element does not occur due to friction, but because of the fit of the teeth of the belt with the pulley. Nevertheless, it has an income below the gears and thus a significant loss of power. The chains also have higher loss power compared to the gears, but this loss is somewhat lower than the toothed belt. The gears are among the solutions, the one with best performance, and consequently less power loss. Therefore, associations between elements with lower incomes were combinations of elements of low and middle/high yield have been considered appropriate, taking score 3, and the principles on which only elements medium/high yield are used were considered good, taking score 4.

The evaluation referent to easy maintenance criterion was performed similarly to the system reliability criterion, so the less complex variants scored higher.

In relation to manufacturing in shortest time, were considered acceptable, scoring 2 variants involving only the use of gears (be cylindrical gear with straight teeth or cylindrical gear with helical teeth) in the two reductions, as demanded large fabrication time, resulting from high complexity of manufacturing the same and enclosure required for this type of transmission, besides the difficulty of implementing this type of transmission in the vehicle.

In situations where the transmission system is configured as a union between a gear set with another element of transmission (CVT, chain or toothed belt), the complexity of the project was reduced, being regarded as acceptable variants, received score of 3. While the projects that gears were not present, the principles were good, scoring 4.

Finishing the stage of pre-evaluation of the variants, the reduced cost of manufacture parameter was analyzed. In this aspect, the project team concluded that the cost to purchase the CVT would be roughly the same in relation to the cost to manufacture the gears of a gearbox. As the cost in question is high because the type of vehicle designed, the variants that have received the combination of these elements were considered acceptable, earning 2. The variants that possessed only one of the two elements were deemed as appropriate, scoring 3. The principles on which was used chains or toothed belt resulted in variants with lower costs, been considered like good, taking score 4. In Table 3 presents the final score of variants in the first Final Score (no weight), which does not consider the weights defined in the criteria tree, and finally, the Final Score (with weight) that considers.

Table 3 – Variants Score

Variant	Final Score (no weight)	Final Score (with weight)
1	28	3,65
2	28	3,65
3	24	3,28
4	23	3,16
5	24	3,18
6	24	3,18
7	NO SCORE	NO SCORE
8	29	3,62
9	24	3,20
10	24	3,20
11	25	3,08
12	25	3,08
13	31	3,60
14	NO SCORE	NO SCORE

According to the explicit on the text, the three alternatives selected for the final evaluation were 1, 2 and 8 variants. It was followed, then a new evaluation of the three variants selected in accordance with the criteria presented in the previous evaluation, but with a more detailed approach. Could notice that the scores given above have almost completely defined the concepts, however, when it undertook analysis of variants with respect to the parameter “easy maintenance”, it was concluded that keeping the gears has a higher complexity compared to maintenance in this, given the chains, when properly selected, require less attention in relation to the maintenance of a system of gears. In addition, the service in the gearbox would slow if it were necessary to dismantle the system for cleaning or replacement of parts. Therefore, the chain remained with good concept, being scored with 4, while the concepts with gears were classified as acceptable, taking score 2. After all necessary summations, Table 4 was prepared containing the final result. According to Tab. 4, observe that the variant that scored highest was the eighth variant, which represents the concept of the transmission system being developed in the preliminary phase of the project. In Figure 6, the representation of concept is presented.

Table 4 – Selected variants score

Variant	Final Score (no weight)	Final Score (with weight)
1	28	3,78
2	28	3,78
8	31	3,81

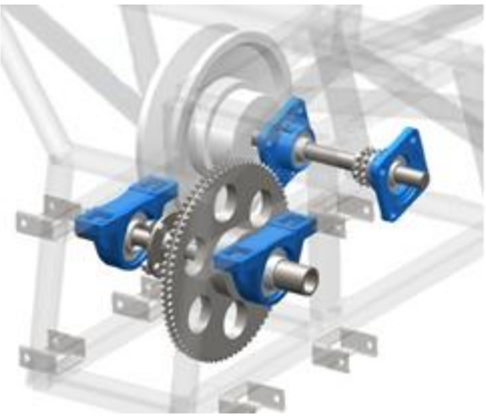

Figure 6 - Transmission System Concept

4.7. FINALS CONSIDERATIONS

Following the methodology proposed by Pahl & Beitz, we realize the common strategy, typical of the German school, that is the decomposition of a complex problem into simples problems. The solution (or concept) is defined by the union of the solutions for each subproblem (Mendes, 2009). Thus, the concept tends to accord for the demand for which was designed in relation with technical, economic and manufacturing characteristics.

Off all the steps proposed in design methodology (informational, conceptual, preliminary and detailed), the conceptual stage is important in the definition of solution principles most appropriate, avoiding minor errors in subsequent stages that has higher cost in production. That is because, in this stage, the whole project concept being developed is defined, and any failure in the selection of the variant may result in a product with low quality and no force in the market. It is noteworthy that the stages of the project have an interactive and iterative relation between them, and, if necessary, return to earlier stages already executed. However, if this is necessary, it can understand that the project was poorly structured, besides causing unanticipated increases in time and costs (Francis et. al., 2002 cited in Li et. al., 2010), possibly leading to a project failure.

5. CONCLUSION

To design a vehicle transmission system was essential to clarify the objective of the project, because the same allowed direct the concept of the project. In the case off a off-road vehicle, the conditions in relation off the performance were key in choosing the solution. This is it observed that the various types of situation, as large variation range of ground conditions and means that the vehicle will be subject. Beyond that, factors such as security and maintenance were necessary to define the concept.

According to the methods for the chosen concept was the variant that has as components a continuously variable transmission (CVT) and a secondary reduction of chains. It was assumed that factors (technical, economic and manufacturing) have been well considered and that the evaluation and selection of the concept were implemented successfully. Therefore, the tendency is that the design team did not encounter major difficulties over the next steps, making it possivle and feasible to create a quality product.

6. ACKNOWLEDGMENTS

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