Int J Interact Des Manuf (2017) 11:155–171
DOI 10.1007/s12008-015-0260-9

ORIGINAL PAPER

From functional prototypes to industrial products

Juan Carlos Hernández-Pérez · **Gilberto Osorio-Gómez** · **Ricardo Mejía-Gutiérrez**

Received: 17 October 2014 / Accepted: 28 January 2015 / Published online: 15 March 2015

Abstract Nowadays, engineering programs with Problem Based Learning methodologies, develop functional prototypes for demonstration purposes. Most of these ideas, many of them promising, are left behind once the academic term is over. Only a slight percentage of them are followed by an industrialization process, which is not formalized and it is based on third-party experiences. Even if well-known product design methodologies include some methods and activities oriented to evolve the product along its life cycle, they are not suitable for academic projects or they leave out some aspects of the local context. This has been an unexploited area, with high potential as there is no transcendence with academic projects; especially after all the time, effort, and creativity employed into a potentially profitable idea. In this way, the authors propose a methodology intended to allow the transition from academic functional prototype to a product ready to be industrialized according to the capabilities of the local context. Emerging economies, where industrial capabilities may be limited. The development of the methodology has been applied in a case study of an individual electric vehicle. This vehicle was developed with students and researchers within the Design Engineering Research Group (GRID) and it is intended to transport the persons responsible to distribute mail, and packages internally in the University campus. The object of such a case is to study the feasibility to promote this vehicle from functional prototype to a product ready to be industrialized under local industrial constraints.

J. C. Hernández-Pérez (✉) · G. Osorio-Gómez · R. Mejía-Gutiérrez
Design Engineering Research Group (GRID), Universidad EAFIT, Cra. 49 N. 7 Sur 50, Medellín, Colombia
e-mail: jherna28@eafit.edu.co

G. Osorio-Gómez
e-mail: gosoriog@eafit.edu.co

R. Mejía-Gutiérrez
e-mail: rmejiag@eafit.edu.co

Keywords Product development · Industrialization · Design engineering · Systematic methodology · Functional prototype

1 Introduction

This research is bred from observed difficulties of industrializing "functional prototypes that are being constantly generated within Product Design Engineering undergraduate program at EAFIT University" [1].

Two widely academically validated product design methodologies like those proposed by Pahl and Beitz [2] and Ulrich and Eppinger [3] illustrate the aforementioned limitations. In a wide sense they both deal with solving an expressed user need by elaborating a design concept and, progressively refining it into a final design solution, fully achievable within an industrial context. Both methodologies have been tested through extensive application in large-scale industry, where corporate areas such as design, engineering, manufacturing, marketing, legal and finance work concurrently throughout the product's design, in order to develop a result that is fully feasible relative to the company's capabilities.

This approach contrasts with the reality of undergraduate students in the Design Engineering program at EAFIT University, Colombia. Whom, regardless of being taught and making regular use of the aforementioned methodologies, simply lack the professional-multidisciplinary knowledge base available in a company. Project results are advanced in terms of design and engineering (the core areas of formation within the program) but relatively immature in other areas such as industrial manufacturing or patenting, vital to large-scale commercialization.

Under such scope, the current relationship with academically validated product development methodologies that students have is one where they solely focus on the design and engineering aspects of either. Though they are open for multidisciplinary input and, by no means, they are forbidden input from different stake holders throughout the product's life cycle, it is a possibility that is implicit within the methodology and not explicit. Since students lack such multidisciplinary knowledge that would enable them to produce such well-rounded design concepts, a more explicit methodology is required in order to guide them, and carry out the necessary steps that enable the industrialization of a functional prototype.

The probability that an idea, produced by a student or group of students, reaches market is currently low within the program. Over the years a small group of ideas have managed to undergo partial of full processes of industrialization. They are in a large sense associated with students undergoing the final stages of their undergraduate career or on the verge of graduation. Students who have understandably more knowledge and experience in terms of producing more industry-ready ideas and whose envision takes them to the next level within their professional life.

The lack of sufficient knowledge and guidance early within the program, results in students often abandoning their ideas once their academic obligations with the project cease. According to administrative sources, the program throughout its seven academic projects produces close to nine prototypes per-project (ranging from furniture to vehicles). In other terms, at the end of each semester there are close to 72 new ideas produced by students. This represents a high opportunity cost when taking into account that outside of academia there is an industrial world avid for new product ideas [4].

The development of a methodology aids in reducing the expressed underlying issue by stimulating the industrial capability of functional prototypes produced within this context; offering new inputs/outputs by taking into account the myriad demands within current industry.

Moreover, increasing market pressure; new demands have driven industry in search for new tools that aid their many business fronts, creating and industrial environment that is open to the input of new ideas.

The proposed methodology is an interactive design process that works within local industrial context, due to the specific constraints of emerging countries, allowing an interactive and collaborative work between different actors of the whole product's life cycle since it encompasses different topics not only related with engineering and design, proposing different tools and methods for specific steps of the process. Vital aspects for industrialization such as legal intellectual property protection, manufacturing definition, and supplier selection, amongst other, are incorporated. Demanding inputs such as a prototype that exhibits all the functional and usability traits of the intended industrial product, and a virtual model (3D-CAD) that digitally describes the entire prototype.

The aforementioned methodology was constructed with a project where a fully functional prototype was developed as a result of an undergraduate final project (graduation project). This project, posing a high commercial upside, was an electric vehicle developed to improve the efficiency of EAFIT University's internal mail delivery.

Taking into account price quotations, Model of selection and evaluation of suppliers (MSEP) program and the information gathered from previous work ties between third-party companies and EAFIT University, a supplier selection is performed. Three suppliers are responsible for the manufacturing of the superior chassis, the inferior chassis and the assembly of the vehicle.

Next chapter introduces a state of the art about methodologies related to industrialization activities, followed by Sect. 3 where the proposed industrialization approach is stated and described in depth. The case study is presented in Sect. 4, followed by some discussion about its results in Sect. 5, and finally the conclusions are presented in Sect. 6.

2 Background

Corporate strategies have been developed within the subject of "concurrent engineering". They support integrated multidisciplinary work through the use of communication technologies and support mainframes. This allows independent divisions within a company, that are involved in a product's life-cycle, to integrate with the aim of "developing new products of the highest quality standards with reduced costs, assembly time, and overall development time", optimizing their capability to be industrialized [5].

The development of each step of the proposed methodology is based on analyzing the interaction between people, the product, the market and especially the industrial constraints of the context where it will be manufactured. This is how a functional prototype must be analyzed, and through the application of the principles of interactive design, it is possible to ensure the manufacturability in the local context.

In this product design process there are some methodologies aiming towards to specific products life-cycle phases [6]. Three of these are related to the process of industrializing prototypes, such as: design for manufacturing (DFM), design for assembly (DFA) and DFTM (design for troubleshooting and maintenance), among other Design for X (DFX) methodologies.

One of the main differences between the developed methodology and DFX methodologies is that "both DFM, and DFA are developed from the notion that production cost is inherently linked and determined by the product design" [7].

For this reason DFX centers primarily in reducing costs, unlike this developed methodology is based on multi-criteria parameters. These are intended to optimize the product not only in terms of cost, but also in terms of time, and quality among others.

In addition, the DFX methodologies are intended to the product design, since they state that "the inability to regard manufacturing and assembly as an integral part of the design stage, can lead towards un-manufacturable products, or highly expensive—unprofitable products" [7].

On the contrary, the developed methodology intends to be a re-design method that allows the refinement of a currently existing design.

Lastly, regardless of the adopted methodology, both DFM and DFA share a constant common purpose. That is to identify designs that are costly or unfeasible early in the design phase, minimize redesign, and reduce total cost required to obtain the finished product [8].

This lines up with two concepts of concurrent engineering. The first is the idea that all elements of a product's life-cycle, from functionality, producibility, assembly, testability, maintenance issues, environmental impact and finally disposal and recycling, should be taken into careful consideration in the early design phases.

The second concept is that the preceding design activities should all be occurring at the same time, i.e., concurrently. The idea is that the concurrent nature of these processes significantly increases productivity and product quality. This way, errors and redesigns can be discovered early in the design process when the project is still flexible. By locating and fixing these issues early, the design team can avoid what often become costly errors as the project moves to more complicated computational models and eventually into the actual manufacturing of hardware [9].

Within such approach there is a series of individual methods and tools that enable the accomplishment of the overall goals previously stated.

Within such methods, theory of inventive problem solving (TRIZ) arises as a systematic approach aimed to analyze challenging problems, or issues where inventiveness is required in order to obtain a solution. Therefor, the method offers a range of strategies and tools intended for such purpose. The theory that supports TRIZ is based on a massive research regarding thousands of inventive patents. One of the main insights that outcomes from this body of work contends "that the vast majority of problems that require inventive solutions typically reflect a need to overcome a dilemma or a trade-off between two contradictory elements". Therefore TRIZ predominantly aims to solve invention difficulties that involved a certain trade-off of compromise between two desirable characteristics. The systematic approach is intended to provide strategies and tools that enable reaching superior solutions that ideally circumvent the need to perform any trade-offs or compromises for the given situation [10].

Along with TRIZ, design for manufacturing (DFM) is also aligned to greatly impact during further stages of the product's life-cycle from a design standpoint. Where TRIZ aims to efficiently solve inventive bottle-necks, DFM tries to prevent delays and inefficiencies in manufacturing. Therefore it can be understood as "the general engineering art of designing products in such a way that they are easy to manufacture". Processes like designing or engineering of a product with the aim of facilitating the manufacturing process is key to eventually cut manufacturing costs. Moreover, manufacturing issues that on further stages would be costly to correct; can be pre-emptively fixed for a fraction of the price within the design stage. DFM sheds light on the fact that the actual design of a part can greatly influence its overall costs.

On the other hand, design for assembly (DFA) arises as a complementary counterpart to DFM, dealing with the effects that part design has on the assembly process rather than manufacturing. Therefore the essence is centered around the idea that products can be intentionally designed to be compliant, and easy to assemble. This last bit reflects of the fact that a product which contains fewer parts will also take less time to assemble, reducing assembly costs in the process. This in turn can be further optimized if the parts contain features oriented to improve their ability to be grasped, moved, oriented and inserted. The reduction of the number of parts in an assembly has the added benefit of generally reducing the total cost of parts in the assembly. This is, usually, the major cost/benefits of the application of design for assembly. Nonetheless DFM and DFA can become mutually exclusive, and contradicting since adding features can lead to more complex parts that are in turn more difficult to produce. A careful examination of the cost/benefit relationship of decisions made utilizing both tools must be therefore present.

Looking further, despite aiding in the generation of designs highly adapted to the manufacturing capabilities at hand, DFA and DFM only account for a limited portion of what it means to industrialize a design/functional prototype. This is can be easily understood by simply listing some of the basic and essential steps necessary to achieve the aforementioned goal, like securing copyright protection, and identifying the most suitable suppliers for raw materials/parts/manufacturing services. DFA and DFM will render a design that is highly optimized for the intended manufacturing and assembly processes, but they simply do not deal with the more logistics, legal and operations oriented tasks within the process of industrializing a design concept. These aforementioned steps might seem menial or trivial to industrializing professionals, and therefore possibly taken for granted in the context of mainstream, large-scale industry, but for first or second year undergraduate students, even recently graduated students they might not be obvious at all; underlining the necessity to provide a methodology comprehensive enough to guide them effectively along the entire process.

3 Industrialization methodology

The methodology being discussed focuses solely on the process of industrialization of functional prototypes produced by undergraduate students of the product design engineering program at EAFIT University. Though the nature and functionality of the functional prototype differ from project to project, they all share as a common core the fact that are all manufactured using the available tools, spaces and manufacturing processes within EAFIT university, as well as materials available within the local context. Moreover such prototypes are intended to serve as real-life validation and visualization of the design concept developed by the students, having a solely academic purpose; being designed to fulfill the needs of a user, but under no circumstance intended to be produced by small or large-scale industry.

The diagram on Fig. 1 illustrates the steps involved in the proposed methodology. Each step serves as a guideline that must be completed in order to advance the prototype into an industrial product.

Individual steps will be further detailed next.

3.1 Prototype analysis

This step is therefore intended to serve as a filter that sorts out whether or not the prototype at hand can be regarded as a "functional prototype".

As previously stated, a prototype defined as a "functional prototype" is the starting point of the methodology.

It can be described as a prototype that exhibits all the functional; usability traits of the industrial product. However due to restraints in budget and manufacturing capabilities, the result is not industrially scalable.

This step in the methodology is therefore intended to serve as a filter (Fig. 2) that sorts out whether or not the prototype can be regarded as a "functional functional prototype".

The aforementioned filter is performed in practice via a series of conditional questions that the entrepreneur must answer in relationship to the prototype at hand. By articulating the aforementioned conditionals into a full statement, a functional prototype under the scope of this methodology can be defined as: "A real-life physical model that accurately represents the functionality, proportions, and materials of the proposed design, employing locally available/manufacturable parts (not parts that are solely available through international shipment), and non-infringing any current copyright protected ideas, designs or products".

Failure to comply with any of the aforementioned statements results in the prototype not being regarded as a "func-

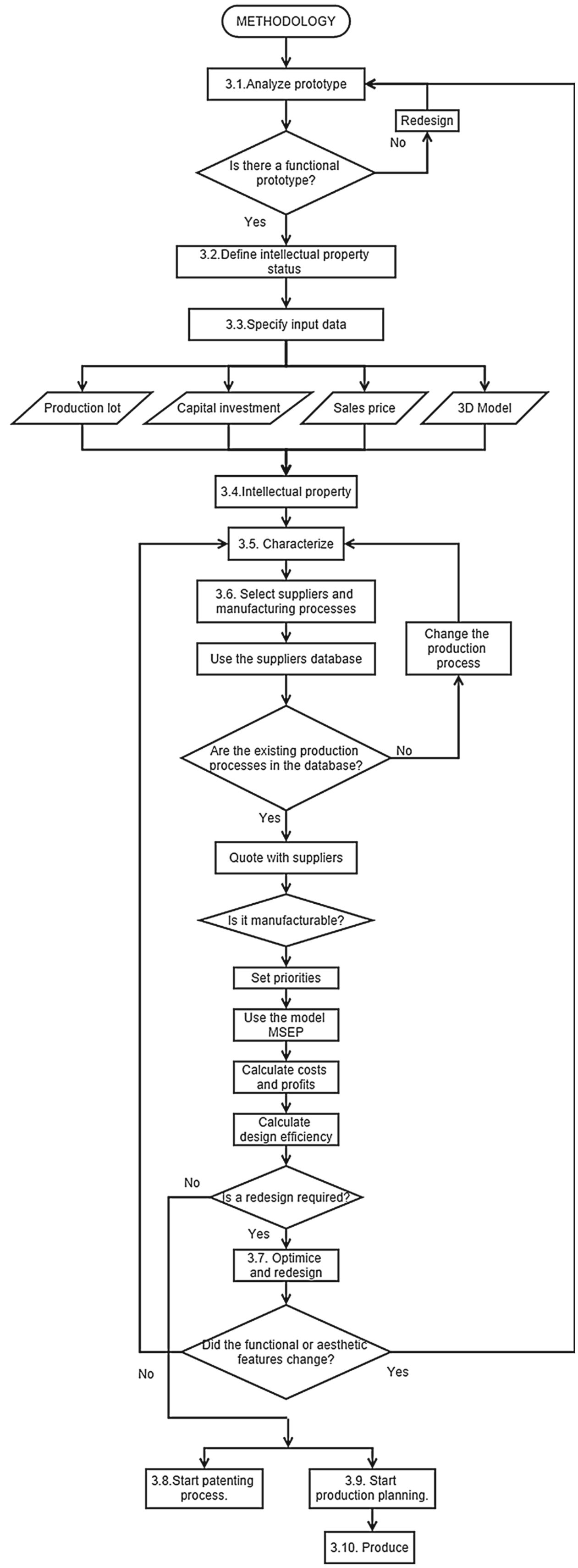

Fig. 1 Proposed methodology

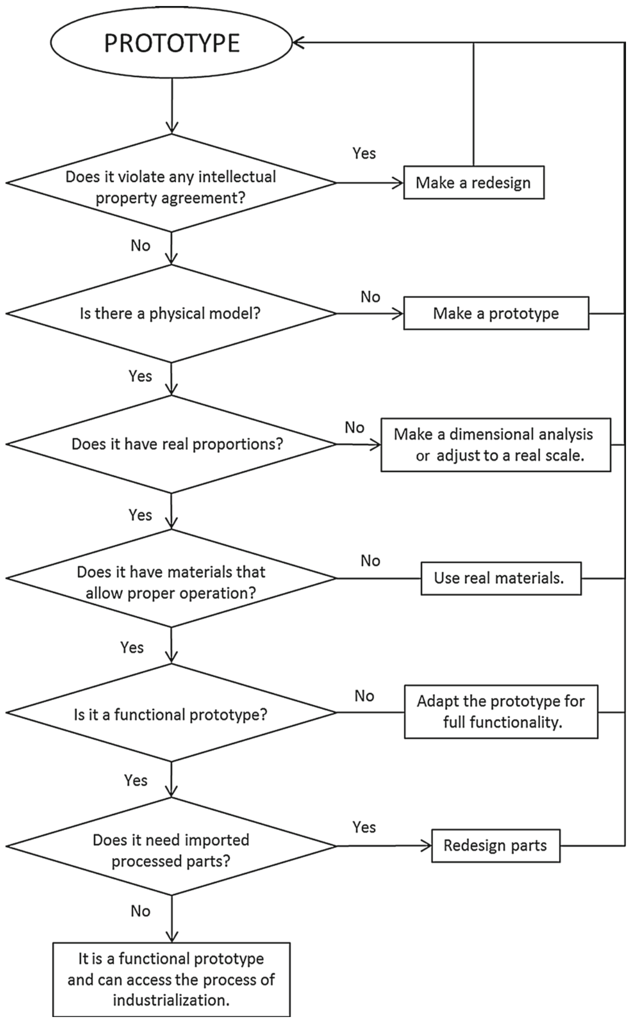

Fig. 2 Prototype analysis—filter

tional prototype" and therefore requiring re-design on any of the items were it does not comply. This must be done if the user wishes to continue with the subsequent steps of the methodology, as a valid functional prototype is the basis of the former.

The former requires the prototype to undergo re-design in order to comply with the categorization. This process can be iterative a "n" number of times until "functional prototype" status is achieved.

Once this is done the process can advance onto the next step.

3.2 Intellectual property assessment criteria

Achieving functional prototype status is significant, as it implies having something usable that properly functions. Besides this, for it to be commercially exploited its legal status as intellectual property must be defined.

This process is thoroughly explored in further segments of the methodology. Nonetheless, the following must be kept in mind.

Recommendations:

- Perform, parallel to the research, a state of the technique analysis; before exploiting the product or process, since what is going to be commercialized might be property of third parties. To undertake this research, it is advised to refer to free on-line data bases [11].
- The invention should not be published, sold, or used before patent application. Otherwise, this might render the idea either ineligible for patenting or prevent the application from being granted [12].
- Ensure non-disclosure agreements are always established and signed before revealing information to third parties.

3.3 Input data

The challenges of producing an industrially feasible product do not exclusively pertain to the realm of design, engineering, and manufacturing. An example is the previously discussed legal aspects. In accordance, "Input data" relates to the business aspects that must be met in order to approach production.

Concretely such aspects are:

- Production batch: The product must be observed and analyzed in accordance with its specified market. The aim is to detect flaws, possible upgrades, and design opportunities; thus refining the product towards industry. It can be seen in the Tables 1, 2, 3.
- Expected capital investment: It is the amount of capital, in Colombian pesos (COP), available to be invested towards industrial production.
- Sales price: It can be theorized by comparing the design to existing products within the same range, and product class. Establishing this is fundamental, since later it will allow calculate the product's profit margin.
- 3D model: A parametric, accurate, and up to date 3D model is of great importance. Manufacturing, assembly, business planning, among others need the existence of the model.

Table 1 Production batch vs market

Production batch	Market
1–100	Small market
100–1,000	Medium market
1,000–10,000	Big market

Table 2 Production batch vs cost

Production batch	Cost
1–100	Small investment
100–1,000	Medium investment
1,000–10,000	Big investment

Table 3 Production batch vs time

Production batch	Time
1–100	Short term
100–1,000	Medium term
1,000–10,000	Long term

3.4 Copyright protection

Taking into account the former recommendations, the methodology intends that the entrepreneur benefits from his/her project or invention through the protection of his/her moral and material interests. For such reason the process of Intellectual Property protection is emphasized, in order to promote progress through new developments that promote innovation, and the transference of technology.

In this way through the functional prototype, the entrepreneur is able to get close to the subject of intellectual property. In this case, be it through the area responsible for this subject within the corresponding university (being advised by experts on the subject) or through web research within official intellectual property agencies, the entrepreneur will be able to expose his/her idea. Being able to determine the interest and willingness/unwillingness to develop the project in partnership. This decision will be made by the corresponding university, who will evaluate variables such as the level of novelty, market potential and technical prowess amongst others (which will vary from institution to institution).

The next step is to identify the corresponding intellectual property registry. Either be it through invention patents, utility model patents, or other registries that are pertinent for the given case. In this way the goal is to proceed and validate the invention aiming towards it being securable, and defining the specific registry that will cover it.

Concluding, it is important to know that this process requires of a significant capital investment, for which is then necessary to obtain the pertinent financial means to develop the project. In case of not having it, the entrepreneur must be able to secure either financing or investment in order to be able to register and protect his/her intellectual property.

3.5 Characterization

Steps up till now deal with project set up, stating and organizing the fundamentals that latter stages build upon. Characterization in turn deals with advancing the functional prototype into manufacturing. This process can be achieved either by allocating a high number of manufacturing operations to a limited range of industrial processes (i.e. example constructing the product out of sheet metal and using only sheet metal folding, bending, and stamping to achieve the final product), or by assigning the full-range of manufacturing operations to a limited pool of manufacturing suppliers. Achieving centralizing benefits by avoiding costly operations incurred when transporting parts from one manufacturing supplier onto the next (i.e. packaging, delivery, tracking, etc.).

This term implies an in-depth analysis of the functional prototype in order to clearly identify the manufacturing nature of all of its parts and components. The objective is to compile data regarding part geometry, material and the manufacturing processes that enables its attainment into standardized documents.

For this, the methodology provides a series of charts that describe production processes, as well as tables that suggest materials for specific process—production lot size combinations [13]. Additionally there is a database that encompasses locally available manufacturing processes.

This step starts with 3D model of the prototype and finishes with the workshop drawings. Each part should be characterized with dimensions, tolerances, unions, or other features that are necessary for its proper understanding. Each of the non-standard parts has its respective drawing and name, in addition to the drawings of each sub-assembly and complete product assembly.

All non-standard parts of the prototype will be characterized with material and process and this information will be tabulated in order to allow data processing for the following steps. In the methodology a characterization table example is provided with all this information.

In order to successfully accomplish this the following set of guidelines are suggested.

Recommendations:

- Quote with minimum three suppliers: This gives context about the industrial offering of the service required; giving an idea about the industry's average value proposition.
- Several suppliers to manufacture all parts: It is very risky for an industrial operation to depend on single suppliers. Any setback from their part will, in turn, mean setbacks and delays in product realization and delivery.
- Centralize processes: Centralization enables more overall control in terms of the whole operation. Under such terms, key assets can be administered more effectively, and costs can be tracked and controlled in order to attain economies of scale.

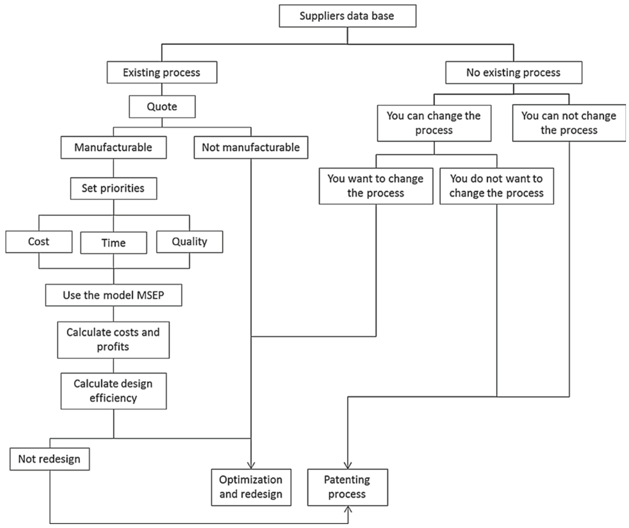

Fig. 3 Selection of suppliers and manufacturing

- Trusted company for assembly: Assembly is a key aspect of production, therefore the one/ones in-charge of providing it must have an ethos of responsibility/dependability.
- Confidentiality agreement: Intellectual property is a key asset central to a company's interests. Outsourcing manufacturing/assembly to third party suppliers always puts at risk sensitive information to fall into the wrong hands. In order to prevent such scenarios these types of agreements provide a legal insurance.

3.6 Suppliers and manufacturing

Following the process of characterization, the selection of the suppliers and manufacturing processes must be undertaken according to the steps presented in Fig. 3.

The following steps should be considered for an existing manufacturing process:

1. Use the database for local suppliers.
   For such purposes a database containing information about available locally based suppliers, discriminated in terms of searchable variables was devised and made available to users. The aim of this database is to centralize and standardize supplier information, it contains a detailed list of possible suppliers; easing comparisons amongst different prospects.
2. Define your priorities.
   Suppliers and manufacturing processes advantages are not absolute but rather relative to the intended priorities under which they are evaluated. Lack of priorities equals a lack of a comparative frame of reference upon which decisions can be made. The following priorities are defined in order to evaluate and select suppliers and related processes.
   - Time:
     The amount of time that suppliers take to answer in an effective and productive manner to the requirements specified by the entrepreneur before and after providing price quotes. An effective supplier is that who accurately hands out the required information within the same day, in a matter of 2 or 3 days.
   - Quality:
     Covers the level of satisfaction that is expected by the entrepreneur before and after obtaining a given part. It depends on the parts price, delivery times, and the terms previously agreed by both parts. This is the most subjective aspect of the three priorities, nonetheless it can be defined by the level of accuracy upon which the supplier meets the part/process requirements stipulated by the entrepreneur. If demands are met between an 85 to a 100 % as of user demands, than the supplier can be regarded as of having quality.
   - Price:
     It is recommended to perform simulation utilizing the price matrix, a tool that aids to visualize the actual cost of a part or process according to the relationship between its monetary value, and the opportunity cost represented by the lead time involved in delivery. If delivery times for partial and total product are clearly stated, than the formerly stated procedure can be performed. Average market prices for a part or service can serve as general guidelines that help assess the relative price given by a supplier, lower prices can imply compromises either on time and quality that enable the lower price, inversely a higher price can imply better service terms and quality. Production lot is a subject that directly influences the monetary outcome of business operations. The production lot must be sufficient to cope with product demands, and do so in a manner that is economically sustainable. Overproduction or underproduction put a risk that can directly hurt net revenues; therefore first and foremost production lots must, with a high degree, meet the real market size of the market that the product is intended to reach. Lot size is divided in terms of small, medium and large-scale markets, with their corresponding brackets of 100 or fewer units, 100–1,000 units, and 1,000 or more units per lot. Per-unit costs have an inverse relationship with lot size (i.e. the smaller the lot, the higher the cost per unit); in contrast the cost of the entire lot rises in direct proportion to the lot size.
3. Model of selection and evaluation of suppliers (MSEP).
   It is the tool that articulates the actual comparisons amongst shortlisted candidates. It is comprised by a series of logic steps; its aim is to perform numerical compar-

isons amongst desired variables that describe the suppliers/process offering. The result is a score that rates the aforementioned prospects.

4. Calculate net cost of product. It is a gross approximation to the product's final price based on material and manufacturing costs.
5. Calculate utility.
   The estimated gross margins upon which expected profits are drawn from.

$$M_g = P_v - C_n \tag{1}$$

where
M_g is a profit margin, P_v is a sales price, $C_n =$ is a net cost.

$$P_v = \frac{1}{N_{pm}}(C_{pm} + C_{sa} + P_r) \tag{2}$$

where
P_v is a sales price, N_{pm} is a total number of units produced during the product's lifecycle, C_{pm} is a total cost assumed by the manufacturer to produce "N" amount of parts, C_{sa} is a sales cost, includes publicity and marketing costs, transportation, shelf space, salesperson salaries and discounts, P_r is a accumulation of all earnings from all units, charged by each individual entity involved in the supply chain: manufacturer, distributor, and retailer.
This equation can be solved in order to determine net earnings, being "Pr" the final earnings:

$$Pr = (P_v * N_{pm}) - C_{pm} - C_{sa} \tag{3}$$

The total cost (C_{pm}) is calculated in the following terms:

$$C_{pm} = N_{pm}(C_M + C_L + C_c + C_W) + C_T + C_{OH} + C_D + C_{WR} + C_Q \tag{4}$$

where
C_M is a material costs per unit, C_L is a per unit costs in terms of manufacturing and assembly labour, C_c is a capital cost per unit not previously included. (i.e: equipment and infrastructure), C_W is a waste disposal per unit, including hazardous waste management along with other non-threatening waste, C_T is a costs incurred once not covered above (i.e. tool costs), C_{OH} is a indirect overcharge costs (i.e. rent, gas, electricity, salaries, taxes, etc.), C_D is a design and development costs, C_{WR} is a products lifecycle support costs, C_Q is a certification and qualification costs.

6. Calculate design efficiency. It is an efficiency calculation based on the Lucas method of DFA, under this scope a calculated efficiency equal or greater than 60 % is desirable. What must be done first is to divide the components that make up the product into: Essential (A) and Non-essential (B) underneath the efficiency of the design must be measured by the following formula:

$$E = \frac{A \times 100}{A + B} \tag{5}$$

As previously stated, the methodology provides a database that classifies local suppliers according to the manufacturing process currently in offer. Therefore it allows the search of suppliers in terms of the characterization previously performed.

This list enables the process of obtaining price quotes for the specific services. Depending on supplier capabilities, and the specific complexity of the parts the provided response can either be positive or negative. A negative means that the supplier indeed performs the service, but incapable of producing the part, and thus quoting a price.

Depending on whether or not there are other suppliers able to manufacture the part at an attractive cost, part redesign can be put into action.

If positive responses are obtained from several suppliers, then specific selection is influenced by criteria such as time, cost, and quality.

These criteria must be articulated within an evaluation matrix that weighs up the criteria according to the selected importance hierarchy.

3.7 Optimization and redesign

The expression "optimization and redesign" relates to manufacturing and assembly aspects considered in the product design. The previous step was aimed towards migrating part production from an artisanal handcrafted approach towards industrial processes. This step however intends to change the parts themselves so they can integrate with those selected processes in a more efficient way.

For such task DFM and DFA are purported as the intended tools, since they deal directly with both aspects.

Design for manufacturing relates to optimizing each component in terms of raw materials, and the number/nature of transformation processes needed to obtain a finished part. The following steps should be considered in order to select the best couple material/process.

DFM recommendations

- Minimize total number of parts.
- Standardize components.
- Employ common parts amongst different product lines.

- Standardize common design characteristics (i.e. hole diameters, thread types, bending radius, etc.).
- Maintain simple and functional designs.
- Design parts to be multi-functional.
- Design parts that are easy to manufacture (without compromising functionality).
- Avoid excessive clearance (dimensional and geometrical).
- Minimize secondary and tertiary operations.
- Utilize unique features offered by individual processes.
- Separate holes in parts that are machined, casted, molded or stamped, in order to obtain a strong whole part.
- Avoid general directions in blueprints such as "polish this surface".
- Dimensions must be specified from surfaces or specific reference points within the part, not from external space.
- Dimensions must use the smallest diversity of surfaces or reference points.
- Design must be as lightweight as possible without compromising strength and rigidness.
- Design tool for general use (unless high production volumes are intended).
- Utilize "generous" chamfers and roundings within molded, formed or machined parts.
- Try to achieve the biggest amount of productive operations without having to re-orient the part.

The manufacturability index (M_i) is a measure that results from multiplying numerical data relative to the costs of producing a part. Such costs are inherent to the pairing of material costs and manufacturing process costs. With the index being a product of the multiplication of a set of variables that range from low to high-cost, the result is that the higher the index, the more costly is the part and in turn the less economically feasible it is to manufacture. This is especially true for manufacturing processes where machining is involved (i.e. milling, drilling, lathing, etc.) since they involve the removal of material in order to obtain the final part. In other words the cost of the part has does not only involve the material inherent to the part, as well as the cost of the process involved in its obtaining, but unavoidable excess waste material.

$$M_i = V \times C_{mt} \times W_c + R_c \times P_c \tag{6}$$

where

M_i is a manufacturability index, V is a component's final volume (mm^3), C_{mt} is a material cost per volume unit, W_c is a waste coefficient, R_c is a relative cost coefficient, P_c is a base process cost.

The relative cost coefficient is the product obtained from the multiplication of a series of factors that influence the inherent cost of obtaining a part from a specific material undergoing a determined manufacturing process. This equation takes into account not only the complexity that arises by pairing a certain material with a certain process, but also the inherent costs represented by involving complex geometries and surfaces, a high degree of precision in terms of clearances and sections, as well as the degree of elaborateness of the surface finish. In other words a complex part, with a high degree of precision, made from a material that is difficult to process will have a higher relative cost, compared to more simply achieved, less-precise parts. Which in turn will be reflected by the a higher numerical value as the product of the formula.

$$R_c = C_c \times C_{mp} \times C_s \times C_t \ or \ C_f \tag{7}$$

where

R_c is a relative cost coefficient, C_c is a geometric complexity, C_mp is a convenience of material-process union, C_s is a minimum section, C_t is a clearance requirements, C_f is a surface finish requirements.

On similar terms design for assembly (DFA) relates to the product structure; the relationship amongst parts. It aims to identify parts, and/or functionalities that are redundant in order to merge them into fewer parts, or eliminate them altogether.

The following aspects should be considered in order to reduce the number of components and ease the assembly process:

DFA recommendations

- Minimize the number of parts (through reduction, elimination, union, redesign).
- Minimize the variability within the parts.
- Develop multifunctional components.
- Stimulate modular assembly.
- Use stock parts and material.
- Avoid making the assembly operator deciding adjustment parameters.
- Design fail-proof parts.
- Ensure accessibility and visibility.
- Facilitate tool access.
- Avoid the use of fastening and calibration tools by designing self-position and fixing parts.
- Eliminate or avoid the need to orient parts.
- Avoid the use of screws.
- If screws are necessary, unify the type of screw or head type.
- Design fitting parts that fasten through pressure.
- Parts must be uniform, of high quality and have tight tolerances to avoid time losses due to incompatible parts or manufacturing defects.
- Avoid parts that are either fragile, flexible, abrasive, slippery, small, sharp, etc.

– Use parts with sufficient rigidness and resistance that allows them to be automatically fed to the assembly line.
– Unidirectional assembly design.
– Design of parts for easy insertion and manipulation.
– Design parts for self-positioning.

Although the order can be of particular choosing, it is strongly advised that DFA follows DFM.

In further detail DFM is composed by tools such as a “manufacturability index”, “relative cost coefficient”, “waste material coefficient”, “material—process convenience” amongst others (SB1).

Regarding the subject of DFA, amongst the several related tools, those pertaining to the “Lucas Method” are to be used.

3.8 Patenting process

In case of deciding towards patenting the idea, the methodology exposes certain concepts and criteria along with a series of steps intended to facilitate the undertaking of the process. The former are fundamented on the guides offered by the Colombian Superintendency of Industry and Commerce, the Ministry of Commerce Industry and Tourism; in relationship with entrepreneurial activities.

Therefore, for the project to be protected through patents, it must present an advantage compared to what is known, and must solve a technical problem. This scope define what a patent is, and which requirements it must follow in order to be protected.

A patent can be defined as a property title granted by a nation’s government. This allocates the holder with exclusive rights to manufacture, sell or use the pertaining invention. In exchange for such rights the inventor is compelled to reveal in detail how the invention is produced and utilized.

The Fig. 4 can clearly illustrate the process and conditions that define whether the item in question can be patented, and the type of patent that it can apply for as well.

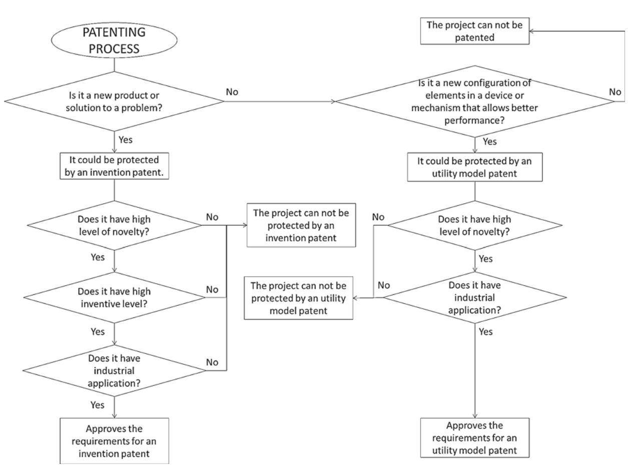

Fig. 4 Process of patent selection

After determining that the project complies with the requisites of and invention or utility model patent, a patent request process is undertaken. For such certain forms and documents are necessary, such as: The petition, the technical document requesting the patent grant, application payment receipt, as well as other documents that might be necessary for the specific case.

As such the applicant requires to have certain practical knowledge of standing legal terms, and carefully follow the process to avoid violating stipulated terms.

Finalizing the application process, once the application form is released in the Industrial Property Gazette; the applicant must request the performance of a patentability test. Under which the Industry and Commerce Superintendency will examine if the invention is patentable or not.

3.9 Production planning

At this point a tightly knit relationship between process, material, and part features has been established. This, nonetheless, excludes how the production as a whole will be articulated. In accordance to this “process planning” is brought forth to close the gap.

Through Gantt diagrams the relationship between “theoretical performance and real performance” of individual tasks, and activities can be graphically portrayed.

Visualizing such information enables decision making by supplying performance feedback, having the potential to alter or shift strategic planning.

Although Gantt diagrams apply to a wide range of uses, the methodology states that they be exclusively employed in production planning and control. This is due to the necessity of having a certain degree of order in shipment delivery time-tables that allows a project’s proper execution. Since outsourcing productive activities to third-parties implies an increased need for tighter control [14].

The use of spreadsheets is recommended since they allow rapid, easy, and effective elaboration of such diagrams. Additionally it is necessary to have certain input data, such as knowing the companies responsible for each one of the activities that compose the totality of the project, set times for each of the activities, dates were they are scheduled to start, and the overall project deadline.

In this way, Gantt diagrams allow the estimation of the lead times in which each one of the activities that compose the project must be executed. If the overall estimated deadline is not sufficient, it should be extended current suppliers should be changed.

3.10 Production

Production is the conclusive stage of the methodology. In a large sense, it encompasses the act of ordering parts, and services from suppliers. There is also further considerations to take into account while producing a product, like transport, storage, and required personnel. Though stock parts and manufactured/assembled parts are supplied by third party companies, the overall logistics, planning and obtaining of the finished product are nonetheless responsibilities only assumed by the entrepreneur and his/her company. In many cases such arrangements can be performed either by the company completing the item or the company receiving the item (for further processes). However this most likely would involve the pay of an extra fee on behalf of the company owning the item, which in the end equates to hidden costs within the production phase.

On the other hand when lots of finished product are delivered, it is necessary to perform tests on samples. This has nothing to do with searching design issues/possible re-design of features or evaluation of the product's performance, but with the assessment of quality within production, and the degree of accuracy that suppliers have with parts/system specifications.

The fact that this phase requires considerable capital input is a given since money needs to be spent in materials, parts, and assembly. Nonetheless operation costs and ownership not only extends to the aforementioned, but rather expand to a wider scope. Outsourcing to third party suppliers and manufacturers improves overall efficiency by taking advantage of their own cost structure and economies of scale, however there are associated costs to this type of operations that might be non-apparent. To name a few raw materials or parts need to be shipped to the supplier's location, supplier relationships need a responsible in order to work correctly (payroll costs), and finished parts need to be shipped back to the company's facilities. Having part or finished product stock also implies ownership costs, since items require facilities that are adequate for their proper storage, adding to the company's fixed costs.

4 Case study

In 2011 the Design Engineering Research Group (GRID), partnering with the Center for Documentary Administration (CAD) and the Headmaster office, developed a project that could improve both the delivery of documents within the university campus and working conditions for CAD employees.

Taking into account to the overall growth that EAFIT University has experienced (both in physical size and academic programs) during the last years, summed to the changes experienced by each one of the internal dependencies; a considerable increment in the volume of internal documentation has been experienced. This has represented and issue for the Center for Documentary Administration (CAD) that is responsible of ensuring that documents arrive accurately and efficiently to all of its destinations. During those times such document deliveries were undertaken by CAD employees, who relied of on pedestrian transportation to reach delivery destinations within campus. When taking into account the increasing distances within campus, generated delays in activities for all dependencies; a negative impact on behalf of documentary delivery.

The Product Engineering Research Group (GRID) with its research line of Electric Mobility, alongside the Center for Documentary Administration (CAD) proposed the realization of an electric vehicle prototype amicable with the environment; and designed to address the issue of transportation between campus buildings. With the goal of improving working conditions for employees responsible for internal document delivery; permitting rapid response to events.

This vehicle was required to adapt to terrain conditions in EAFIT University's campus, portraying a light frame which would foster transport within campus in a non-adverting way; thus minimizing the disruption to pedestrians that transit and share space with the vehicle. Thus in the end optimizing the performance in the delivery of internal documentation, enabling employees to fulfil their tasks in less time.

After thoroughly analyzing journeys, terrain, distances, lead-times and slopes within the university's campus, sufficient input data was obtained to define requirements for designing the electric vehicle. An important fact is that of the 15 km that employees walk, 9.3 km are journeyed outside of campus buildings. This is a 62 % of total journeys that no longer would be needed to be traversed on foot. For this reason the vehicle is designed to perform travel outside of building within open spaces of the university's campus. In conceptual design stage, different components and mechanisms that could conform the electric vehicle were explored. Evaluation matrix results were employed to determine which concept would be ideal, and engineering calculations focusing on: battery calculations, motor calculations, and finite element analysis (FEA) of manufactured parts (chassis and mechanisms) were executed. After these the construction of a prototype used to verify overall measurements; ergonomics was undertaken. It was not built out of the product's definitive materials since it was a fast approximation used to validate geometry. Feedback gained from this version allowed the construction of a working prototype, and thus the result can be seen on Fig. 5.

Below it can be observed how this functional prototype undertook each and every of the steps comprehended within the aforementioned methodology, as well as the final result.

4.1 Prototype analysis (filter)

Beforehand it was clear that the prototype was fully functional, validated through a test phase with end-users during 6 months.

Fig. 5 1st prototype

Table 4 Prototype analysis (filter)

Question	Answer
(a) Does the design violates any intellectual property agreements?	No
(b) Is a physical model of the design available?	Yes
(c) Does it have feasible geometric and dimensional proportions?	Yes
(d) Was it built using materials that allow the proper functioning and operation of the prototype?	Yes
(e) Does it allow to experience the product's operation?	Yes
(f) Does it allow to test and validate basic functions under conditions similar to real operation?	Yes
(g) Does the prototype require of imported parts for its construction?	No

Table 4 presents the proper response given to each one of the questions comprehended by the initial screening held within the methodology. In this way prototype is functional in order to be able to start the industrialization process.

4.2 Evaluation of intellectual property criteria

Each and every of the recommendations proposed by the methodology were evaluated.

- State of the art: This study met excellent results, demonstrating that although similar products do exist, nothing within the search matches the proposed idea. This fostered the parallel undertaking of a formal invention patent petition. It is worth noticing that before starting with the industrialization process an industrial design registry was performed for the vehicle.
- Considering that this invention could be subject for a future patent, it was never showcased outside EAFIT University facilities.
- Confidentiality letter: This document was elaborated by one of the University's attorneys in order to prevent future legal issues with companies who, in posterior stages, would be involved with third-party part manufacturing.

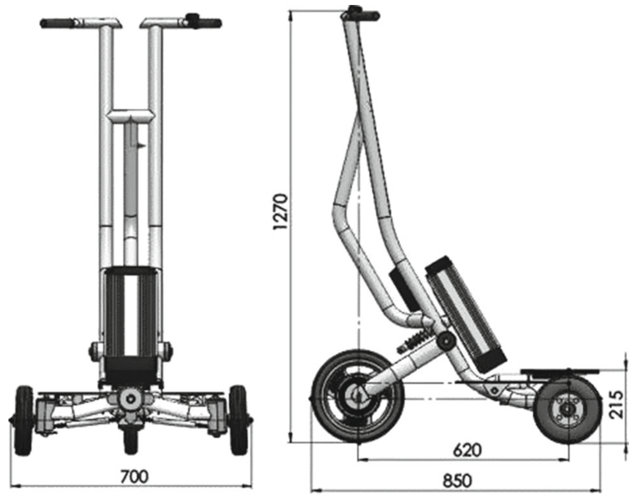

Fig. 6 1st 3D model

4.3 Input data

- Batch: It was initially estimated that for this type of product there was a potentially small market. Additionally there was not initially a large sum of investment capital readily available for the production of early units. Therefore the initial lot was of ten units.
- Estimated capital investment: Initially it is to be assumed that a capital of 50 million Colombian Pesos (approximately 25,000 usd) is available.
- 3D model: This requirement was accomplished to perfection since the design of the vehicle was performed within a 3D virtual environment, where emphasis was put into refining the model and blueprints. It can be seen in Fig. 6.

4.4 Copyright protection

In this particular case work was performed in close relationship with the area, within EAFIT University, responsible for handling intellectual property, the "Center for innovation, consulting and entrepreneurship". As previously mentioned, an industrial design registration was filed, and patent elaboration works were initialized in partnership with a law firm with expertise on the subject. The writing of the patent application was performed in parallel to the rest of the industrialization methodology steps.

4.5 Characterization

The result of this step is presented in Table 5 where each of the manufacturable components of the vehicle are described.

Another result of the characterization step are blueprints, ready and under optimal working conditions for the production of the prototype.

4.6 Suppliers and manufacturing

The Model of selection and evaluation of suppliers (MSEP) tool, was used to support and facilitate the selection of suppliers for prototype industrialization in Medellín city.

This tool provides results depending on the client's requirements, where prices can effectively be calculated as well as service-level and/or quality; fundamental aspects in any type of product manufacturing enterprise. This method also allows the entrepreneur to understand local industry, and find some support for product optimization based on new ideas and experience.

– Supplier Search:
  To begin with the process of selecting suppliers with the MSEP tool, it was necessary to have a clear view of the processes and materials necessary for the development of the project. Having them previously defined each of them was inserted into the program's filter.
  In this way the program generated 11 suppliers matching criteria for the one or more selected processes.
– Price Quotes
  With the intention of protecting the project, a confidentiality agreement letter was elaborated. It was attached by mail to suppliers establishing a commitment to not share information related to the project.

Table 5 Characterization table

#	Part name	Quantity	Material	Process
1	Superior chassis	1	1020 CR steel	Conventional cut: tubing
				Laser cut: sheetmetal
				CNC bending: sheetmetal, tubing
				Lathing
				Welding
				Painting
2	Inferior chassis	1	1020 CR steel	Laser cut: sheetmetal, tubing
				Lathing
				Welding
				Painting
				Milling
3	Foot rest	1	1020 CR steel	Laser cut: sheetmetal
				CNC bending: sheetmetal
				Welding
				Painting
4	Hub	2	1020 CR steel	Laser cut: sheetmetal
				CNC bending: sheetmetal
				Lathing
				Welding
				Painting
5	Wishbone	1	1020 CR steel	Conventional cut: tubing
				Laser cut: sheetmetal
				CNC bending: sheetmetal, tubing
				Lathing
				Welding
				Painting
6	Axle-bar	6	1020 CR steel	Lathing

Calculating net cost of the product through price quotes: With the addition of total final costs of all price quotes:

$$\begin{aligned}\text{Product Net Cost} &= \text{Superior Chassis}\\ &\quad + \text{Inferior Chassis}\\ &\quad + \text{Stock Parts} + \text{Assembly}\\ \text{Product Net Cost} &= \$4.490.000\ \text{COP (About 2.210 USD)}\end{aligned}$$

Considering a profit margin of 34 % and a sales price of \$6.016.600 COP. the profit margin is \$1.526.600 (about 751 USD)

Since the obtained result is positive, the product is able to generate profit. However must be subtracted other additional costs to that margin. Depending on the selected business model.

– Design Efficiency Calculation

The totality of parts that make-up the product, are considered and classified into essential and non-essential components; evaluating their functionality in the product. In this case 14 components were considered, of which, nine were considered essential and five non-essential.

Therefore, the Design Efficiency was calculated with Eq. (5), where $A = 9$ and $B = 5$, obtaining 64.28 % of design efficiency.

This indicates that according to the LUCAS method, the design is good, since the result exceeds the recommended 60 %. Thus the prototype can be considered as totally functional enabling it to be launched to market. However in order to test the whole methodology it was decided to go on with the proposed steps and continue to the re-design stage.

– Supplier selection

Taking into account price quotations, MSEP program and the information gathered from previous work ties between third-party companies and EAFIT University, a supplier selection is performed. The former process lists three companies responsible for the completion of the entire vehicle, one responsible for the superior chassis, another for the inferior chassis and finally the third one will assemble the entire vehicle.

– Supplier evaluation

From the responses given by selected suppliers it was easy to notice how the season and time margins influenced the fact that the stage of manufacturing and assembly of the vehicle could not be performed in the initially proposed schedule (late November–early December). It can be concluded that is necessary to have in mind time on which suppliers delay response, since capacity, technology and personal/time are not always necessarily available. Nonetheless, they were kept in contact with the intention of giving continuity to the process and achieve the completion of the construction of the vehicle.

It is important to clarify that knowledge about the processes offered by the different supplying companies was achieved. Contact with the companies allowed to reach a stage of price quotes and order approvals, where the companies were able to get familiar with the project. They provided their time capability, personnel, and technology in order to fulfil what the entrepreneur required through the design's blueprints.

It is noticed, of the few companies that actually quoted, one gave a price quote that according to them was proportional to the opportunity cost of the season; which in turn was deemed as too high in relationship to the University's payment capabilities.

In contrast, other company, that has yielded good results to other projects of the University, delivered a much clearer price quote that contains a more rational description of payment conditions. Therefore it was desired to continue the process with that supplier.

At this point the prototype is completely functional and it could be launched to market as a product without undergoing any type of changes, re-design or optimization. Nonetheless for purposes concerning methodology testing and implementation, it was decided to undertake proposed posterior steps and initialize the re-design phase of the methodology.

4.7 Optimization and re-design

Following each one of the steps and recommendations that are proposed within the methodology regarding design for manufacturing and assembly, various upgrades and modifications were performed on the vehicle's design, obtaining a second 3D model of the prototype. The second 3D model can be seen in Fig. 7.

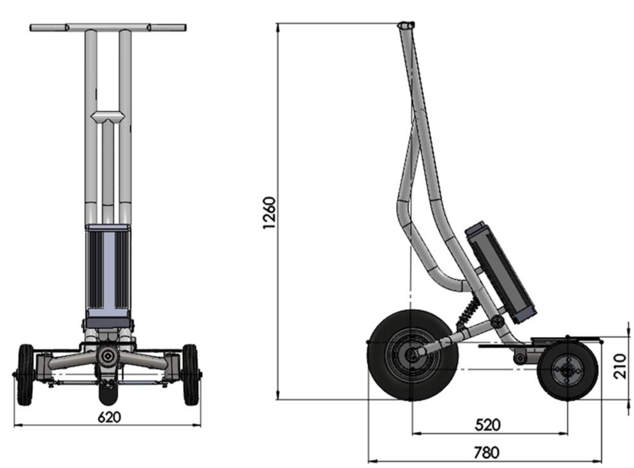

Fig. 7 2nd 3D model

Table 6 Comparison chart—number of standard parts (SP) and manufactured parts (MP) between 1st prototype and 2nd prototype

	Prototype 1	Prototype 2
MP	107	84
SP	92	81
Total	199	165

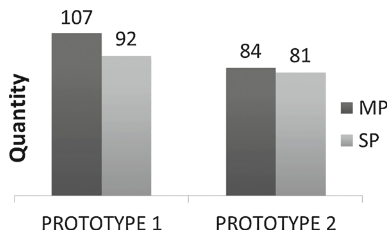

Fig. 8 Number of standard parts and manufactured parts

Table 6 compares the number of components for both prototypes.

After applying the design methodology to the first prototype, a decrease of 21.5 % and of a 12 % was obtained on the required amount of both manufactured and stock parts, respectively. The difference between 1st prototype and 2nd prototype can be seen in Fig. 8.

A change from 199 parts to a 165, represents a 17 % overall decrease in total number parts belonging to the prototype.

Table 7 indicates the reduction of manufactured parts (MP) for each sub-system. There are a total of 12 sub-systems that conform the vehicle, both for the first and second prototypes. For instance, the load-support was initially assembled from five different manufactured parts. Contrasting with the second prototype's, load-support is only composed of a single manufactured part. This was achieved by integration of the footrest with all three of the other parts involved, to form a single one. On the other hand, new parts had to be added to the second prototype in order to save weight as well as costs.

Table 7 Comparison of MP and weight between 1st prototype and the 2ndprototype

	Prototype 1		Prototype 2	
	MP	Weight (kg)	MP	Weight (kg)
Superior chassis	46	9.9	22	5.8
Inferior chassis	21	7.4	15	3.4
Fork	13	1.7	12	0.9
Foot rest	6	3.5	4	4.7
Load suport	5	2.2	1	0.0
Hub	3	0.6	4	0.7
Steering	1	0.2	1	0.1
Washers	4	0.4	10	0.7
Cap	3	0.8	8	0.5
Axle	3	1.4	3	1.3
Separator	0	0.0	2	0.2
Bronze bushing	2	0.4	2	0.3
Total	107	28.6	84	18.6

If two of the largest sub-systems of the vehicle are evaluated (inferior and superior chassis), it can be observed that the superior chassis constitutes a 52.2 % reduction in the amount of total manufactured parts, whereas the inferior chassis represents a 28.6 % reduction on such parts. Nonetheless there are sub-systems that instead of removing components, gained them; as was the case with the amount of washers and caps required to complete the second prototype. Anyway, an overall weight reduction was achieved relative to the first prototype, correlating with the fact that overall manufactured parts fell by a 21.5 % margin. It can be seen in Fig. 9.

One of the most remarkable achievements of the re-design process was the total weight reduction achieved on the second prototype. The first one weighed 28.6 kg relative to its manufactured parts. After being subjected to the methodology a 35 % weight loss was achieved, resulting in a weight of 18.6 kg in manufactured parts for the second prototype.

As with the previous chart, the following chart converges on the fact that the most significant weight savings were related to the inferior and superior chassis sub-systems. The former underwent a 58.6 % weight reduction, while the first shed 54.1 % of its weight. This can be seen in Fig. 10. While the first version weighed 41.6 kg, the second one weighs 31.6 kg (including electronic components).

Design Efficiency Calculation, is obtained with Eq. (5), where $A = 11$ and $B = 2$, obtaining 84.61 % of design efficiency.

In this way it can be concluded that taking into account both recommendations for optimization as well as re-design under the methodology the final design has the potential of significantly boosting efficiency, going from 64.28 to 84.61 %.

4.8 Patent process

The entire patent process underwent parallel to the industrialization steps and all of this work was done in alliance with a law firm and the patent is currently registered with the number 14-093.164, in Colombia. It must be taken into account that after patent application is granted, it is necessary to pay an annual fee to maintain it.

4.9 Production planning

In this stage a diagram showcasing companies responsible for each-one of the activities was prepared, showing in detail the tasks or activities pending by each part, date on which the company initiates the building process of the part that is

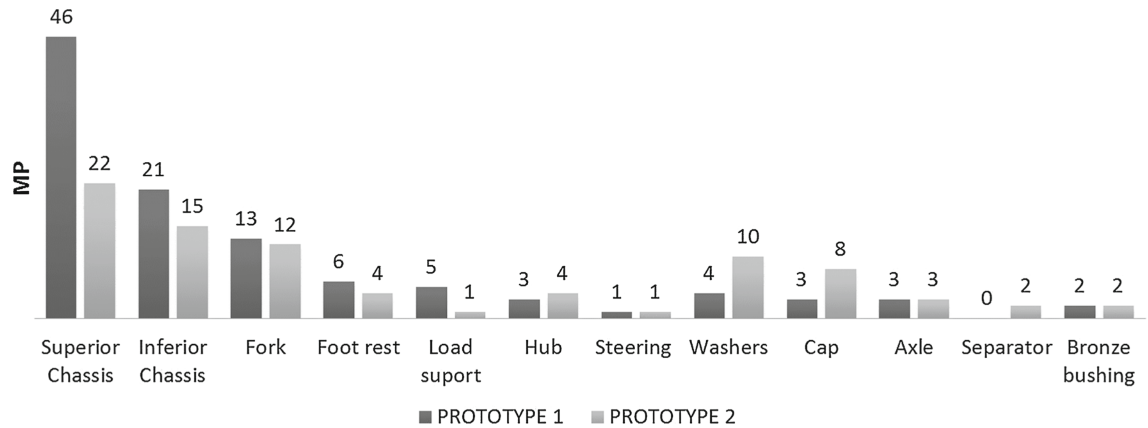

Fig. 9 Comparison chart between 1st prototype and 2nd prototype—parts manufactured

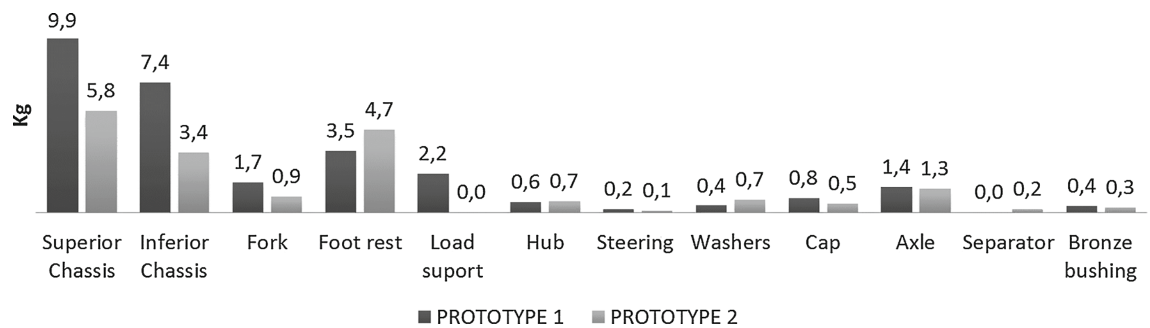

Fig. 10 Comparison chart—weight of parts manufactured in 1st prototype and 2nd prototype

assigned to provide; the lead-time between initial and final estimated delivery date. For this case two companies for the manufactured parts, which were grouped in two main sub-assemblies, one company for the stock parts and one company for the assembly process of the whole prototype were selected. This approach has considered a characterization assigning the full-range of manufacturing operations to a limited pool of suppliers in order to centralize activities.

4.10 Production

As seen in Fig. 11, the second version of the prototype was scrutinized upon delivery in order to assess the characteristics and quality of its finished components and overall build. These measurements and observations need to be logged in order for it to be available for decision-making regarding either future production operations (i.e. management of suppliers) or for future projects to rely and build upon.

5 Discussion

This methodology is a tool that allows students to take their academic prototypes, and transform them into a feasible industrial product. It is important to waive the methodology from responsibilities related to the product's market success, since this falls short from its scope.

The case study reflects such approach since it begins with a functional prototype, and ends with a feasible industrial product. This project was born of academic purposes, serving as the subject for a thesis for the Product Design Engineering undergraduate program.

As such, the initial prototype was built in an artisanal, handcrafted way that obeyed restrictions in industrial capability. By applying the steps that the methodology encompasses, and nowadays the university counts with a vehicle that serves its internal mail system.

Although the product is not commercially available, the several units under service do perform under real use conditions. This proves its validity as an industrial product by being reliable, reparable, and replaceable, through quality build, spare parts, support and efficient production.

The fact that it is being deployed and used means that intellectual protection had to be put in place beforehand. Since by its very definition an invention cannot be used prior of being patented. Its innovative nature, market potential, and visibility within EAFIT justified the intellectual protection process underwent by the vehicle.

The decision to take this particular electric vehicle as a study case is due to it is promising potential of being sub-

Fig. 11 2nd prototype

ject to industrial and commercial escalation. Therefore, the design has undertook the design methodology with very satisfying results up to this point.

6 Conclusions

This methodology is directed to undergraduate and graduate students from the most basic, to the most advanced levels. Nonetheless it must be noted that some of the tools presented within the methodology can be of an advanced nature, and therefore possibly challenging for the more inexperienced students.

Asserting that the methodology is applicable and successful for each and every case is still far-fetched given the reduced amount of information.

Therefore a phase of extensive tests is currently required in order to harness a significant sample regarding results, and effectiveness of the approach. In addition this type of testing could also reveal possible issues with the methodology, and, in general terms, aids in its tuning and refinement.

Finally it is important to emphasize that the objective of the methodology is to translate an object defined as a "functional prototype" into an industrially feasible and scalable product, which can be commercially exploited by its owners, or a third licensing partner. Further results and consequences of market introduction and sales do not pertain, and can not be directly co-related with it.

Acknowledgements Authors would like to acknowledge EAFIT University for the financial support to achieve this project. Special thanks to the Internal Documentary Office from EAFIT University to participate in the prototypes testing program. Authors would also like to specially thank the undergraduate students involved in the development of the project: Alejandra Gómez, Valentina Orjuela, Federico Arbeláez, Mariana Tamayo, Juan David Velásquez, Juliana Montoya.

References

1. Gutiérrez, R.M., Gómez, G.O.: Integrated design and development of complex systems under a PLM approach: a sustainable transportation system case study. Latin American and Caribbean. J. Eng. Educ. **6**(1) (2013)
2. Pahl, G., Beitz, W., Feldhusen, J., Grote, K.-H.: Engineering Design: A Systematic Approach, vol. 157. Springer, London (2007)
3. Ulrich, K.T., Eppinger, S.D., Goyal, A.: Product Design and Development, vol. 2. McGraw-Hill, New York (2011)
4. Universidad EAFIT: Pregrado en IngenierA-a de DiseAño de Producto. http://www.eafit.edu.co/programas-academicos/pregrados/ingenieria-diseno-producto (2013). Accessed Nov 2013
5. Canciglieri Jr, O., Kovalchuk, J.P.B., Rudek, M., de Souza, T.M.: Development of white goods parts in a concurrent engineering environment based on DFM/DFA concepts. In: New World Situation: New Directions in Concurrent Engineering: Proceedings of the 17th ISPE International Conference on Concurrent Engineering, pp. 491–501. Springer, London (2010)
6. Filippi, S., Cristofolini, I.: The Design Guidelines Collaborative Framework: A Design for Multi-X Method for Product Development. Springer, London (2009)
7. Boothroyd, G., Dewhurst, P., Knight, W.A.: Product Design for Manufacture and Assembly. M. Dekker, New York (2002)
8. Cherpakov, B.I., Cross, C.E., Herold, H., Ing, A.K.D., Kannengiesser, T., Priem, D.M., Riedel, F., Ing, M.S.D., Todtermuschke, M., von Hofe, D. et al.: Manufacturing engineering. In: Springer Handbook of Mechanical Engineering, vol. 10, pp. 523–785. Springer (2009)
9. Kusiak, A.: Concurrent Engineering: Automation, Tools, and Techniques. Wiley, New York (1993)
10. Altshuller, G.S.: The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity. Technical Innovation Center, Inc. (1999)
11. WIPO: PCT. http://www.wipo.int/portal/en/ (2013). Accessed Sept 2013
12. sic: Patentes. http://www.sic.gov.co/drupal/patentes (2013). Accessed Sept 2013
13. Swift, K.G., Booker, J.D.: Process Selection: from Design to Manufacture. Butterworth-Heinemann (2003)
14. Fang, Y., Du, L.: Gantt chart generation technology based on web applying in manufacturing execution system. In: Recent Advances in Computer Science and Information Engineering, pp. 303–308. Springer, Berlin, Heidelberg (2012)