AN ACADEMIC DESIGN METHODOLOGY FOR ELECTRICAL MOBILITY PRODUCTS –FROM NECESSITY TO FUNCTIONAL PROTOTYPE

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ABSTRACT
The undergraduate program in Product Design Engineering at EAFIT University-Colombia, includes an applied project course during eight semesters with different topics. Students attend their last project course in seventh and eighth semester integrated into one year topic. In this project, they have to design a new high-tech consumer product in electrical mobility for different types of transportation need and to construct a completely functional prototype. The objectives of these courses are to focus on the triad of "Product-User-Context" as well as to foster design, engineering, manufacturing, management and entrepreneurship skills. In order to offer a systematic way of working, and to obtain better results, a systematic design methodology has been adopted, adapted and applied during the whole product development process in order to facilitate representation, analysis, calculation, management and control of the information related to the product. The methodology is broadly explained through activities, tools, information and results related to four main stages: 1) Need research & problem statement, 2) Conceptual design, 3) Detailed design and 4) Prototype construction & testing. A successful case study is presented following all the stages of the presented methodology for the development of an Electric Power-Assisted Bicycle.

Keywords: Electrical mobility, Product design engineering, academic design methodology

1 INTRODUCTION

The undergraduate program in Product Design Engineering (PDE) at EAFIT University-Colombia was established in 1999 under influence of existing European academic programs in Italy [1], Spain [2] and Netherlands [3], and it is oriented to the combination between engineering with its technical and scientific base (inventiveness and project management) and the industrial design with its social and human aspects (aesthetics, manufacturing technologies and graphics), leading to the application of new technologies, use of computer tools for engineering analysis, acquaintance of critical and scientific thought, innovative projects with social relevancy, teamwork and proactivity of the students. So, pointing to this learning objective, each student attends a biannual course, called "Project X", during eight semesters, where they are called to apply their current knowledge developing new consumer products starting from a real need and finishing with a functional prototype of a new and innovative product. For the first six semesters, each Project course has an identified necessity and sector but for the last two project courses of the program, Project 7 and Project 8, the main topic is Electrical Mobility. Here the students are engaged to identify real needs in different sectors, to design a successful hi-tech product and to construct a completely functional prototype following a proposed systematic methodology. All of this focused on the triad of product, user and context and to foster manufacturing, management and business skills in the students. For each project course there are three tutors with expertise in different disciplines in order to complement and support the different phases of the whole development of the prototype. In this way, a student from the Product Design Engineering program is the only one in Colombia, at the moment, to get involved in the development of multidisciplinary projects each semester in contrast with other engineering programs. The students attend these project courses at a rate of about 40 persons a semester.

2 PROPOSED DESIGN METHODOLOGY

In order to offer a systematic working way and to obtain better results, an academic design methodology has been established to be followed by students in those courses. Such methodology has been adopted and adapted from well-know methodologies just like systematic design by Pahl and Beitz [4], product development by Ulrich and Eppinger [5], design process by Ullman [6], total design of Pugh [7], Design for Assembly and Manufacturing [8], Integrated Product Development by Andreasen [9], and Concurrent Engineering philosophy [10]. Multidisciplinarity is obtained from integration of conventional design theories from industrial design (e.g. aesthetic and ergonomics), economic viability analysis from business area and need analysis from marketing field. Besides, different Information and Communication Technologies (ICT) are proposed and implemented during the product development process in order to allow representation, analysis, calculation, management and control of the whole information related to the product.

Next, the methodology is broadly explained identifying activities, information and results for the four big stages identified: need research and problem statement, conceptual design, detailed design and prototype construction and testing (See Figure 1).

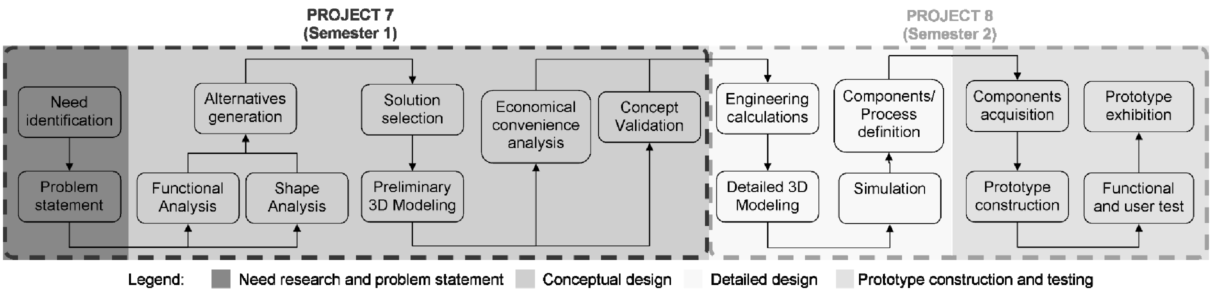


Figure 1. Adopted Design Methodology

2.1 Semester 1

2.1.1 Need research and problem statement

For the need identification the tutors assign three different segments that are considered of interest where the work team must detect possible mobility problems. The encountered necessities are justified by real and supported data and analyzed from market, technical and product perspectives. Eventually, an evaluation matrix is developed with the most relevant parameters, in order to identify the necessity with the most potential for the project's development, bearing in mind though, that the course objective is not to copy existing products but to generate an innovative solution. This phase ends with the creation of a Project Brief, which contains the research results and properly justifies the selected necessity, and a Product Design Specification-PDS Chart with specifications derived from requirements of clients, capabilities and standards.

2.1.2 Conceptual Design

Based on a synthesis of the identified need, the work group conducts a functional and aesthetical analysis that helps to conceptualize the ideas and elements that will determine how the product will work and look. The tools used for the functional analysis are functional structures and flow charts which are analyzed by breaking-down the product's operation into sub-functions that define possible components as well as the technologies required for their implementation.

Alongside the functional analysis an aesthetical analysis is conducted, based on information obtained in the study of the user, the context, the state of the art of similar products and trends in shapes, materials, colours and so on. These define attributes that the product must have as well as the language and/or semantics to develop a shape exploration. Eventually there must be a generation of different product architectures with drawings, sketches and renderings to show different design configurations that will be evaluated to determine the most appropriate according to the PDS and the scope of the project. To avoid a biased and subjective selection of the best design alternative there must be an evaluation matrix that includes an array of objective assessment criteria.

With a complete design alternative selected the next step is to create a parametric 3D CAD model and technical drawings. This model will eventually permit the configuration of a 1:1 scale model

supported by Augmented Reality to display different configurations of colour, texture, accessories, terms of use and anthropometric diagrams, among others.
The product concept must be validated from an economic perspective. The fixed and variable costs must be analyzed based on the number of units planned for possible sale or its market demand. For this each group should consider not only its potential market, but also the budget to produce the product in 2 different scenarios. Each group will argue whether the concept is suitable for a viable business idea.
Finally, each group must correct and/or modify the PDS according to the changes experienced by the project and prepare a final presentation by defining the brand identity of the product, developing various informative posters and putting up a stand to promote the project results.

2.2 Semester 2

2.2.1 Detailed Design

The design team starts with an engineering approach in order to calculate product performance. As this project is oriented to electrical mobility, each team formulates the problem to state the force, torque and power required. Then, batteries pack can be estimated also and selected in order to fulfil PDS requirements (e.g. Speed, driving range, etc.). Once this is settled, the power control is designed as well as all electric components that are going to be included (stop lights, indicators, battery level, etc.).
After having designed the basic functional components, the product architecture is revised and team proceeds to create a detailed 3D model in CAD software. All components are modelled in detail and assembled in a top-down approach.
With this model, students are asked to evaluate the system under multi-physics Finite Element Analysis (FEA). Each of the different design decisions must be justified experimentally and/or by a numerical analysis (well documented) with high engineering rigor.
After they finish validation cycles by simulation, at this point they may obtain the final render of product proposal. This is the virtual proposal of what they are going to build.
Once the model is finished, each team must create all technical drawings (blueprints) necessary to manufacture the product, with dimensional and geometrical tolerances in accordance with the selected manufacturing process. This includes assembly and sub-assembly drawing with component lists and corresponding references to the BOM table.
Students should also prepare a list of manufacturing processes for the prototype, as well as a list of manufacturing processes for the product. They have to clarify what are the considerations or assumptions taken into account for the prototype construction, and the implications for the mass-production of the final product determining the scale economies that may occur considering volume discounts and/or the implications of wasted materials. They have then to assess feasibility of manufacturing and draw conclusions.
The final stage is the Product and Prototype Cost Chart. The team will include two cost tables detailing all different components that give the total cost (raw material, labour, outsourced processes, etc.). Each item must be adequately justified by quotations, invoices, etc. supporting the estimated cost. A concluding activity refers to compare these results to what was established in the PDS and the cost implications on the prototype and product feasibility.

2.2.2 Prototype construction and testing

At this point, some of the most expensive components (such us Hub motors, Batteries and in some cases the Control Unit) may be provided to the students by the University. For the complementary set of raw materials and components, students search for sponsoring which sometimes comes from private industry in money or sometimes from materials or components providers who donate their products. Once the team has obtained materials, they start constructing in the University's manufacturing laboratories by themselves.
Students are able to build the functional prototype that represents the concept defined in the detailed design, using materials that, although at a certain percentage, may not be those originally proposed in the design, but able to resist the mechanical stresses of normal product use. **Prototype is the central element of the project**. It must coincide with the dimensions, assemblies and construction details presented in the technical drawings. The prototype should be delivered with its corresponding User's

manual that describes and summarizes the requirements and criteria necessary for the care, handling and maintenance of the developed product.
Together with the prototype, students should prepare the “Product Test Plan”. It is a set of protocols to perform standard “Technical tests” and “User Tests”. Technical tests are those whose purpose is to verify product’s technical operation, as well its performance under working conditions similar to those at product will be exposed to. User tests are those whose purpose is to observe users reaction to product use, as well as interaction between user and product. These tests intend also to check ergonomic and aesthetic aspects of the product. Test results are documented in the form of technical report attaching the photographic record, collected data, calculated results, analysis and conclusions. Students are asked to prepare the report, according to the “Communications in Engineering” chapter from “The engineering design process” book [11].
Finally, at the end of the semester each team prepare the product launching in a general exhibition of students’ projects. This launch takes place on the final delivery date (after 18 weeks of work). The exhibition stand has to be prepared not only as product’s launch platform but also as an opportunity to attract investors for a later stage of project development.

3 CASE STUDY - ELECTRICAL MOBILITY PRODUCT

A successful case study is presented for the development of an E-Bike. In this exercise, an electric hub-motor (350W-48V), electronic controller and electric bike batteries 6-DZM-12 (12V-12Ah) have been provided by the University and the rest of components have been designed, selected and acquired by the work team. This work has been sponsored by a local company from the motorcycle sector. Next, a brief description of the principal activities and results for each of the main four stages are presented.

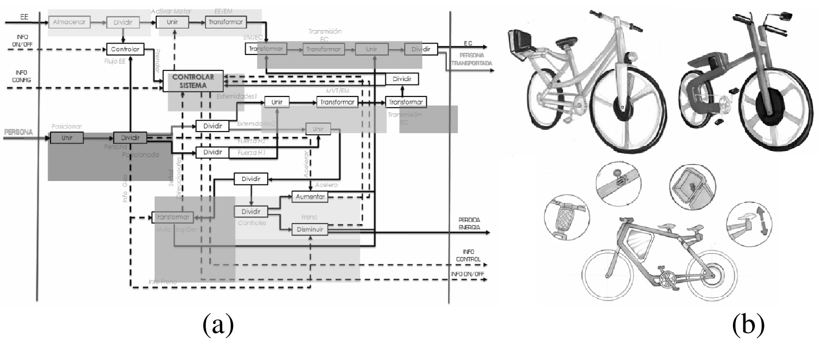
3.1 Semester 1

3.1.1 Need research and project brief

The project starts with the analysis of mobility problems in three different market segments: security, private transportation and public transportation; devoting special attention to real needs that could be considered like business opportunities for new and innovative products. At this point, three different mobility necessities have been identified and evaluated from technical, product and marketing aspects. The work team has identified a personal mobility problem for users with a worker profile, middle age and belonging to low-income family; and the context has been defined as the urban areas of the Medellín city. Finally, the mobility project has been configured with a Project Brief and a preliminary Product Design Specification format.

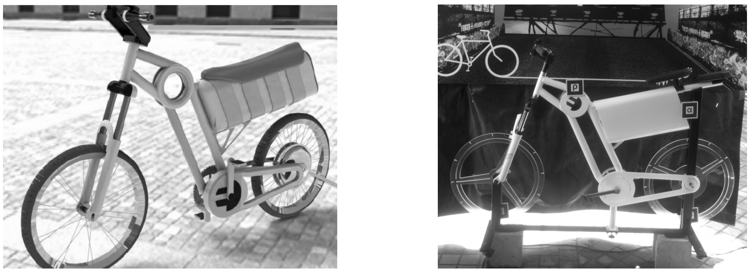
3.1.2 Conceptual Design

Starting from the general problem statement, the work team has simultaneously developed a functional analysis identifying mechanical, electrical and control sub-functions (Figure 2b).
A final solution has been selected through a matrix evaluation and its preliminary 3D conceptual model (Figure 3a) has been generated in order to be evaluated, in different possible configurations, through a 1:1 physical mock-up assisted by Augmented Reality (AR) technology (Figure 3b). Concurrently, an economic viability analysis has demonstrated the feasible success of the product for a subsequent detailed development in the next semester.



(a) (b)

Figure 2. (a) Product Functional Analysis and (b) some sketches for alternative solutions



(a) (b)

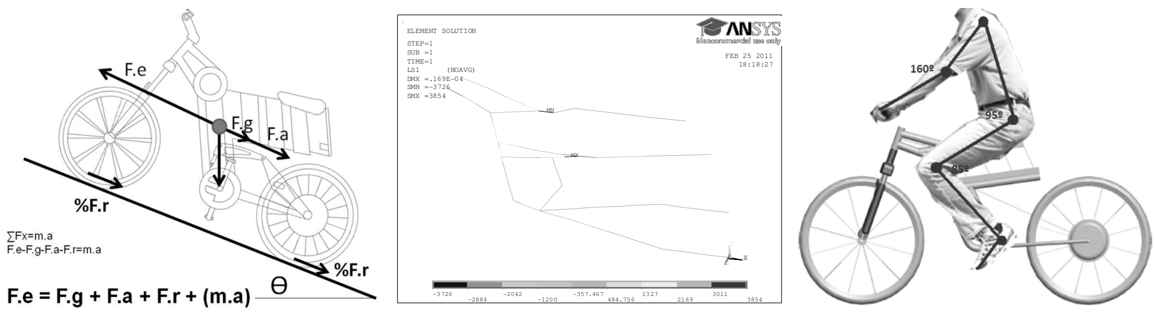
Figure 3. (a) Preliminary rendered 3D model and (b) Physical mock-up for AR validation

3.2 Semester 2

3.2.1 Detailed Design

This semester begins taking up all the information of the previous semester again and reorganizing the work team with new fellows. The project brief and the PDS are revisited and the final concept solution is controlled by the tutors considering production feasibility and prototype construction.

So, the work team is dedicated to all the engineering considerations, starting from a revision of preliminary calculations for power and driving range (Figure 4a). Then, more specific engineering calculations are carried out in order to define materials, standard components and production processes and the available electric and electronic components are tested and additional functionalities are analysed. At this point, a detailed modelling of the final product (Figure 5a) is developed considering all the components and with this model final controls are carried out for engineering simulation making use of computer tools (Figure 4b) and for ergonomic and user-interaction analysis (Figure 4c). Besides, technical drawings with dimensions, tolerances and annotations are generated for further construction of the functional prototype. With all the information now available, a detailed economic viability analysis is performed in order to identify the final cost of the product related to acquisition of standard parts, manufacturing and assembly. Such analysis has considered a marketing study, real production processes and ROI; supported by data from the local stakeholder. Besides, the work team propose the different technical and user tests that the functional prototype should pass according to national and international standards.



(a) (b) (c)

Figure 4. (a) Engineering calculations, (b) Finite element and (c) Ergonomics analysis

3.2.2 Prototype construction and testing

With all the information validated, students proceed to the standard parts and raw materials acquisition. At this point, an obstacle arose. Main components (Hub Motor, Control Unit and Batteries) did not arrive on time. The importation of these components was made by the enterprise that sponsored the project, but delivery had a delay because of a customs problem. For this reason, components that were considered for the design had to be changed on a last minute decision for other components with different specifications (for example wheel diameter and motor power) that were available at company's facilities. As a consequence, planned performance was not as designed and aesthetics was affected as available Hub Motor had a smaller diameter (as it can be compared between Figure 5a and Figure 5c). Consequently front wheel diameter had to be changed too.

(a) (b) (c)

Figure 5. (a) Rendered virtual model, (b) technical tests and (c) Real functional prototype

After solving this issue, the prototype construction and technical and user tests were carried out in the University facilities (Figure 5b) a week before the final exhibition. Such tests yield information for tuning of the prototype that is finally presented to the University community and industrial and governmental guests (Figure 5c), in order to observe the impact of such academic projects oriented to the improvement of private mobility in the city. For this particular E-bike, the general comments have been positive and academic and external third parties are interested to kick-start the process of industrialization for this product.

4 CONCLUSIONS

The PDE program devotes its teaching methodology to an integral education where students are concerned with different working areas of the product development process, from marketing to functional prototype construction and testing. As the electrical mobility market is still under development around the world, but with high potential in Colombia, the implementation of this design methodology has delivered a lot of feasible and promissory product ideas for local market. One key lesson learned is that reliability of main electric components (motors and batteries) is still a weak point for Colombia as there are no local manufacturers. All those components have to be imported from China or USA constraining time of development and sometimes quality. However, successful ideas have been identified as ideas with potential to be further developed as industrial products for new or existent enterprises. Current functional prototypes have increased their quality and reliability compared to former projects from these courses. Additionally, the final exhibition has showed that this event attracts industries and individuals interested on new product ideas. It is an important platform for local innovation and students can propose their ideas to local investors or in many cases they continue as entrepreneurs in order to create a company around their ideas.

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