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GENERIC PRODUCT DESIGN & VALIDATION METHODOLOGIES AT THE DETAILED DESIGN STAGE

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Abstract

Doing design is to imagine and specify things that don't exist, with the scope of modeling them and bringing them into the world. The «things» may be palpable-machines, buildings and bridges; they may be procedures-design methodologies for an organization or protocols for a manufacturing process, or for solving a scientific research problem by experiment; they also may be works of art-painting, lyrics, music or sculpture. Engineering design can be challenging and exciting, or it can be taxing, difficult and unproductive if the validation methods of the product are not linked to the client needs and to the product specifications. Uncertainties and variability always exist in design predictions. Loads are often variable and inaccurately known, strengths are variable and sometimes inaccurately known for certain failure modes or certain states of stress and other uncertainties may result from variations in the quality of manufacture, operation conditions or maintenance practices. One of the objectives of this paper is to outline a methodology that highlights the exciting challenges of product design and allows both engineers and students to focus on the development of a creative, effective and profitable solution. Another challenging goal of this paper would be to integrate **design optimization** and **design validation** at the detailed design phase in the product development process. Detailed design involves interactions between three elements: **geometry**, **materials** and **loads**. In this context, links between these elements will be formalized in terms of design methodologies. The optimization process allows finding one or more combinations of parameters maximizing or minimizing a given design criterion, while the validation activities provide feedback to the designers in order to verify the calculations accuracy and the achievement of all design criteria. To provide safe, reliable operation in the face of these variations and uncertainties, it is common practice to utilize the design safety factor and to integrate it into the product development process (PDP).

Keywords: Product Development, Product Design, Design Situations, Generic Product Design, Validation Methodology

Introduction

The particular frameworks described in this article are elaborated because they have the potential to satisfy two objectives of engineering design: to ensure consideration of each of the elements necessary for a successful design and to ensure that all the consequences of the application of the designed device or process throughout its lifetime are examined [1]. For almost all products, it is no longer acceptable to develop major enhancements without first consulting customers to forecast the market acceptance of the improvements [1; 2]. The risk is just too high to accept one product manager's belief in their «feel» for the market. Rather, a team must apply statistically sound measurement methods of a product's intended customer population [2-4].

It is critically important to understand the competition and the trend of any new technology introduction into the market [4]. It is also important to design robust performance into a product, so that the product is as high quality as possible given its price. These goals and associated methods have become the competitive weapons that allow design teams to ensure that their company leads the market [1-4]. The problems encountered in product design are amenable to many solutions. There will always be more than one way to proceed, and there will certainly never be just one «correct» solution or design. The designer also cannot assume that he has the best answer just because he has an answer that appears feasible [2].

Given the fact that in the existing literature few articles describe the iterative process by which a concept is developed into a product in accordance with the specifications data and current tools support, the design and validation methodologies proposed will focus particularly on the detailed design phase. More specifically, considerations should be given to detailed design methodologies that target multiple design criteria and adapt to various design situations. The detailed design phase in the product development process will also include both the product optimization and the product validation [5].

In the next sections (2 and 3) the product design process will be presented as part of the product development process and several design situations encountered in this process will be detailed.

Product Development Versus Product Design

A product development process is the entire set of activities required to bring a new concept to a state of market readiness [2]. This set includes everything from the initial inspiring new product vision, to business case analysis activities, marketing efforts, technical engineering design activities and development of manufacturing plans [4]. Often it even includes the development of the distribution channels for strategically marketing and introducing the new product [4].

A design process is the set of technical activities within a product development process that work to meet the marketing and business case vision [2]. This set includes refinement of the product vision into technical specifications, new concept development, embodiment engineering of the new product and the validation of the product design at each stage-gate of the design process [2]. Neither the product development process nor the design process encompasses all the subsequent manufacturing process when the products are physically made [2; 3].

However, the design of the manufacturing process is generally considered part of the product development process. Often the product design process and the design of its manufacturing system must be carried out simultaneously [3].

Similar to the manufacturing process that follows the product development process, there are also front-end activities that are required before product design and which, based on industry, may or may not be considered part of the product development process [3; 4]. For example, the Research & Development (R&D) phase of a new product development is when a new technology or a new methodology is developed for subsequent incorporation into products [1-3]. Today, large companies in many industries try to separate the R&D process from the product development process [2]. Thus, R&D efforts create new technologies and methodologies and develop them to the point where both technologies and methodologies are encapsulated into a new system ready for immediate adoption by the product development teams.

A systematic effort and the contents of this paper are devoted to formalize the activities of a design and process at its detailed phase depending on the design situation by isolating each activity, understanding what is required as input, what is produced as output and then establishing optimization loops to repeatedly complete the activity [5; 6]. Product development then becomes a very rapid process of tailoring technologies into a new system that meets changing market needs without getting bogged down into researching how to obtain a new technology and/or methodology that does not really perform what is expected in the end [5; 6].

However, the product development process requires that engineers define the type of prototype or model, its use, and so forth. Often it is also important that the team decides how to implement a prototype or a model of the final product [2].

Generally speaking, a model is a representation that can be used to answer a question or set of questions [2]. This model may be anything from a no feasibility experiment to a fully developed performance expression over a feasible range of product design variables. The definitions of prototype and model sound enough alike that it prompts a question: Are prototypes and models the same thing? The answer is «not exactly» [2; 5]. The distinction between prototypes and models may have more to do with the intent behind their making and the environments in which they are tested than with any clear dictionary-type differences [2-6]. Prototypes are intended to demonstrate that a product will function as designed, so they are tested in their actual operating environments or in similar, uncontrolled environments that are as close to their relevant «real world» as possible [2-6]. Models are intentionally tested in controlled environments that allow the designer to understand the particular behavior or phenomenon that is being modeled.

For example, an ATV prototype is made of the same materials and has the same size, shape and configuration as those intended to run in off road. An ATV model would likely be much smaller. It might be tested in laboratory, but it is not a prototype [5].

Moreover, prototypes and models have different roles in engineering design because of their intents and test environments [3-5]. The decision to build a prototype depends on a number of things, including: the size and type of the design space, the cost of building a prototype, the ease of building that prototype, the role that a full-size prototype might play in ensuring the widespread acceptance of a new design, and the number of copies of the final artifact that are expected to be made or built [6-9]. Little and Dym [7] provide an interesting approach that compares the design and testing of airplanes to that of buildings. This approach has to do with the number of copies being made [7; 8]. The design spaces of both aircraft and high-rises are large and complex. There are literally millions of parts in each, so many design choices are made along the way. In this case, the complexity and expense of building an aircraft prototype don't argue directly against the idea of building such prototypes. Also, we build prototypes of airplanes because those particular planes are not simply thrown away as «losses» after testing; they are retained and used as the first in the series of the many full-size designs that are the rest of the fleet of that kind of airplane [7-9].

Buildings failures are rare in part because high-rises can be tested, inspected, and experienced gradually, as they are being built, floor by floor [7-9]. So, the answer to the question «When do we build a prototype? » is «It depends on the design field on the type of product and on the design situation ».

Types of Design Situations

In this section, a classification of four design situations is proposed with the aim of providing to students and to designers a good understanding of the main design situations that they could meet throughout their careers.

Otto and Wood [2], present in their book the design situations as original, adaptive and variant design. The authors [2] provide a generic approach regarding the design situations and they just say that an original or new design is equivalent to an invention [2; 4]. In fact, *an innovation* corresponds to the introduction of a new or significantly improved item in terms of its characteristics or intended use [2-4; 7]. *Adaptive design* involves adapting a known system to a changed task or modifying a significant subsystem of a current product [2]. This type of design does not require a massive restructuring of the system within which the product operates and which is the reflection of the demands of the marketplace [2; 4]. Another approach founded on existing references is *the redesign*. Redesign does not mean adapting design. Rather, redesign only implies that a product already exists that is perceived to fall short in some criteria and for which a new solution is needed [2].

In the context of this paper, *new design* involves elaborating new solutions for a given task. The result of a new design could not necessarily be an invention but it has to be original. For example, a new ATV (All Terrains Vehicle) light fixture can be a new design but it will not be an invention. The designers will generate a totally new geometry of the product (so it is original), but we cannot say that it is an invention [5].

Contrarily to the new products*, an evolution from an existing product* is when a product is modified or improved by adding new functions or simply a new geometry starting from a reference product that already exists [5]. This type of design dominates the vast majority of design activities [5]. Customers generally want new products that fit in their current life-style. Within the boundaries of this life-style, their ways of using the product evolves along with the technology [2-6]. Meeting these evolving needs and boundaries can be very profitable with minimal risk. An example of this approach would be the face-lift of an ATV.

Variant design involves varying the parameters of certain aspects of a product to develop a new and more robust design. Thus, several parameters could be changed in this case: size, geometry, material properties, etc.). This type of design usually focuses on modifying the performance of a subsystem without changing its configuration. It is also implemented when creating scaled product variants for a product line. For example, a bicycle resized to a larger load rating will require greater critical sections on the fork and on the frame. This approach (variant design) regarding the design process was identified during our researches and a specific methodology has been developed (see section 5) with the aim of providing technical and logistical information as well as for the first two approaches presented above [5].

Selection of the Design and Validation Methodologies in the Product Development Process

The need to formalize the design and validation process at its detailed phase has been identified both in the industrial and academic fields. Thus, to improve the communication and the transfer of information between all actors involved in the product development process, a common vulgarization describing the activities of design and product validation has to be established [10].

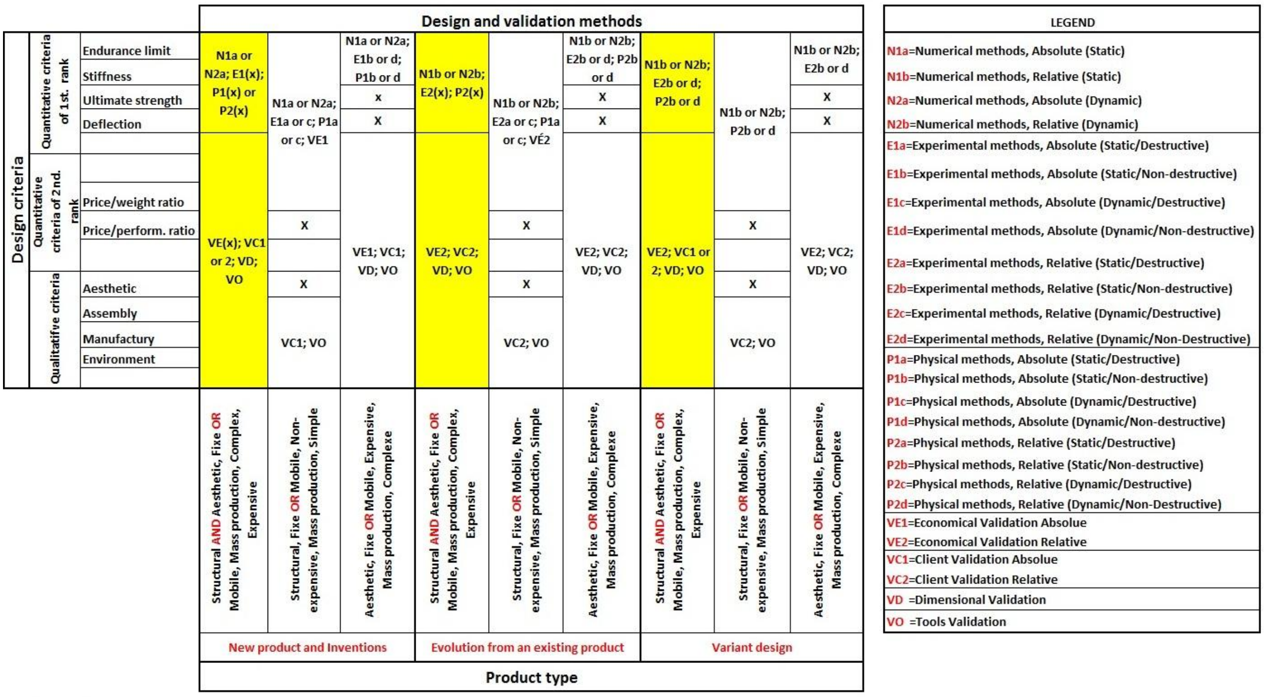

Figure 1: Selection table of product design and validation methodologies

Types of Product Criteria

The selection table shown in Figure 1 was built to meet the need described above and it synthesizes several types of activities at the detailed design phase of the products development process. These activities are based on design criteria established at the preliminary design phase and on product types. Thus, three blocks in close interaction are identifiable in the selection table: (1) Design Criteria, (2) Product Types and (3) Design and Validation Methodologies [11-12].

On the left of the table, several design criteria have been chosen. To better organize the stages of criteria analysis, a classification into three categories of these design and validation criteria is provided: (1) Quantitative criteria of 1$^{st.}$ rank, (2) Quantitative criteria of 2$^{nd.}$ rank and (3) Qualitative criteria.

The quantitative criteria of 1$^{st.}$ rank have been defined as the mechanical, quantifiable criteria with a direct impact on client safety or product integrity throughout its life. The analysis of such criteria will always require a safety factor to ensure that the use of the product will be done while safeguarding the user and in compliance with any applicable safety standards.

The quantitative criteria of 2$^{nd.}$ rank are the design criteria related to the economic dimensions of the product. They are very important for the commercial success of the product on the market. The analysis of this type of criteria is required to determine whether the functional solutions found are economically viable, while still meeting the quantitative criteria of 1$^{st.}$ rank. In order to avoid the circumvention of certain quantitative criteria of 1st rank, it is very important <u>not</u> to <u>make</u> the analysis of the quantitative criteria of 2$^{nd.}$ rank before the analysis of those of 1$^{st.}$ rank.

The qualitative criteria are defined as any non-quantifiable design criteria of a product. As Figure 1 shows, this category of criteria encompasses the paradigm «Design for X». By integrating the analysis of quantitative criteria in the activity flow of the design process, multidisciplinary teams will become familiar with the paradigm of «Design for X». Thus, the number of errors detected at the prototyping phase, or even on production or assembly lines will be significantly reduced.

Product Types

In the selection table shown in Figure 1, the most common combinations (non-exhaustive) of product characteristics have been identified. Based on these characteristics, designers will know which design and validation methodology is most appropriate for their designs. First of all, three main categories are identified and they are detailed in the third section of this paper: (1) New product, (2) Evolution from an existing product and (3) Variant design. Then, for each category mentioned above, several additional features were added in order to properly determine the profile of the product.

In the first stages of the design process, engineers should determine whether the product developed is a structural part or if it is rather an aesthetical part of a system.

Moreover, a designed product may be both structural and aesthetic at the same time (ex.: a vehicle body), it could also be only structural (ex.: a vehicle frame) and yet it could just be aesthetic (ex.: a projector glass). A structural product requires an analysis of loads and the calculation of a safety factor, while an aesthetical product will not undergo mechanical loads if not only the environmental impacts such as sun, rain, freeze and thaw, etc.

But if only the characteristics presented above are to be considered, the range of products will be too large and it will be impossible to envisage a tailored design methodology for each product. To exemplify the idea, we consider two different products: a frame and a steering arm. Both are structural products, but the complexity of a frame could broadly exceed the complexity of a steering arm. Thus, for a complex product, analysis criteria will be sought and numerical simulations will be made, while for a simple product, analytical calculations will be sufficient to reach a suitable solution. Therefore, to choose the best design and validation methodology, the profile of the products has to be further developed and the level of product complexity has to be well established.

The economics also plays a very important role in the product development process and engineers must keep track of the expenditures incurred by the product at all stages of its development process [13]. Product complexity can affect costs, but it is not necessary or possible to assess a product cost simply based on its complexity. For example, there may be a simple product but a design variable, such as the choice of material, which can make the product become much more expensive. In this case, a deeper economic analysis will be required. However, if the costs of material, equipment or manufacturing process are not high, the product will be identified as a cheap product even if its geometry is complex.

Finally, the last features to be used for «shaping» the profile of a product are based on the number of items produced after launching the product on the market. Here we identify five cases: (1) reduced series, (2) mass production, (3) prototype and reduced series, (4) prototype and mass production and (5) prototypes. By knowing these possible characteristics of the product, the engineers will be able to better anticipate the costs and delays in the product development process. For example, for a mass product (more than 100,000 items) engineers should provide an appropriate lifetime for the tools (injection molds, cutting and bending tools, etc.) and plan for the cost of their replacement. Moreover, if a prototype is required during the design process, the expenses and delays incurred in the development process could increase depending on the complexity of the tasks required at each phase of the product prototyping [14].

Design and Validation Activities

The third block of the selection table provides information regarding the appropriate design and validation methodology corresponding to the product type selected and to the chosen design criteria. All eligible methods have been symbolized and framed in the middle of the table and a legend was created to provide the information concerning the symbols used in the table. The selection table presents seven main categories of design and validation methods which are: *(1) numerical design and validation, (2) experimental design and validation, (3) physical design and validation, (4) economic validation, (5) client validation, (6) dimensional validation and (7) tooling validation.* These approaches will be detailed in the next section.

The terms *«static»* and *«dynamic»* are used in this paper to provide general information regarding the types of the activities performed inside a design and validation step with their own complexity and deadlines. In the context of our research, design and validation methodologies for static loads are related to the calculations, analysis and testing of a numerical or physical model or product for which the amount of external forces and moments is considered zero. In the same context, the design and validation methodology for dynamic loads are used in calculations, analysis, simulations, experimental setups and under real life condition testing, where cyclic or combined loads are considered. Generally, in the case of a structural product, the static analyses are performed at the detailed design stage to identify the critical sections of a structure (product). Then, a dynamic analysis (fatigue) is needed to determine the corresponding lifetime of the product under development [15].

Finally, the terms *«destructive»* and *«non-destructive»* added in the legend for experimental and physical design and validation methodologies, provide, to those involved in the product development process, the information regarding the nature of the tests to which the product will be submitted. If the test is destructive, the product will be tested until it fails in severe conditions and the results will be analyzed according to the shape of the fracture, whereas in the case of a non-destructive test, the product performance will be analyzed under normal conditions of use, which should not cause its failure. The tests Euro-NCAP represent a good example of *destructive* tests that aim to analyze the behavior of several structural parts of a vehicle after various impacts which could occur during its functional life. On the other hand, the experimental tests used to verify the behavior of a headlamp in a vibration environment are considered as being a *non-destructive* validation methodology.

Each design or validation activity is very important to assess the client needs and they can also be expressed along two dimensions, depending on clients needs and on design situation: *absolute* and *relative* design approaches. For example a client can express a desire concerning the weight of a product component. This requirement can be *absolute*, when the design criterion is a value that must be respected (ex.: max. 50 kg.) or *relative*, when the design criterion is expressed as a wish of the client (ex.: the lightest in the market). Moreover, when the engineers analyze the loads applied to a new product, they have to establish a new service load cycle. In this case, they are dealing with an *absolute design* approach. On the other hand, when an existing product represents a design starting point for an improved product, the engineers will take in consideration the initial service load cycle of the existing product to establish the new loads applied to the product. This would be a *relative* design approach.

The next section of this paper will propose three workflow diagrams which integrate the most relevant combinations of design criteria and product types identified in the recreational product industry,. These workflows were developed in the scope of the main design situations identified in this industry: (1) new design, (2) evolution from an existing product and (3) variant design.

Generic Design an Validation Methodologies based on different design situations:

Based on the approaches presented in the 3rd section and those developed in the 4th section of this paper, three generic design frameworks (methodologies) are proposed. They represent an improved synthesis of all stages of the design process at the detailed design phase, including the product validation stage. Depending on the design situation (see the 3rd section), each of the proposed methodology should act as a roadmap for designers as it specifies the activities to be made at each phase of the product design process.

Design and validation methods include discipline-specific CAD (computer aided design) and means including formal design reviews, public hearings (if applicable) and testing.

Thus, during the design communication (usually performed at the end of the design process) the multidisciplinary teams will document the manufacturing specifications and their justifications. <u>Proposed design and detailed specifications</u> represent the inputs for this step.

The main task is <u>the documentation of the final design and t</u>he outputs at this level of the design process are <u>the final written and oral reports to the client containing:</u> (1) the drawings and design details and (2) the fabrication specifications.

The feedbacks from clients and users, and itemized lists of required deliverables represent the source of information for the design communication.

The design and validation methodologies proposed in sections 5 could be considered as a checklist which can be used to ensure that all the required steps have been dealt with.

Checklist like this can be used by design organizations to specify and propagate approaches to design within their firms.

Design and Validation Methodology for a New Product:

Figure 2 shows the steps to follow by the design team from the modeling stage of the product until its final validation phase. The methodology is generally applicable to structural products from the recreational products industry (frames, handlebars, forks, bumpers, etc.) for which a detailed study of their service life is required.

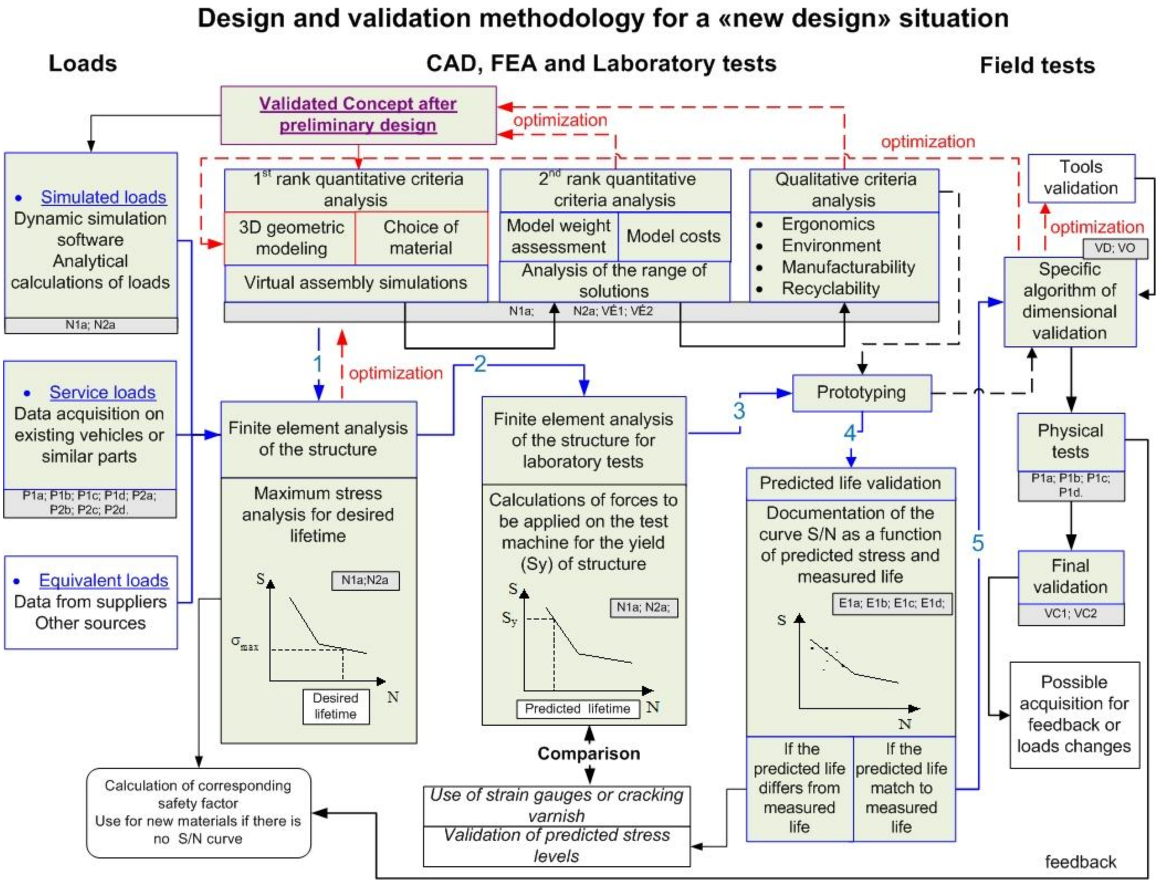

Figure 2: Design and Validation Methodology for a New Product

As the methodology shows, there are activities related to the validation process that can be made at the detailed design stage or earlier. For example, several tools for gathering data loads can be used before the steps of criteria analysis. For this design situation, three types of data acquisition methods have been identified: (1) virtual method *(simulated loads)*, (2) experimental method *(service loads)* and (3) benchmarking methods *(equivalent loads)*. The virtual method uses simulation software to determine the dynamic loads on a product under certain conditions (speed, weight of the product, etc.). Using the experimental method, data acquisition is made with strain gauges, applied to existing vehicles that have been developed either within the organization or among competitors. The benchmarking method uses data available from components suppliers or other sources, such as feedback provided by the dealers following the repairs during the warranty period, etc. These data could also have been obtained using one of the two previous methods outlined above (virtual and experimental methods) or following the analysis of a failure that occurred during the use of the product.

As illustrated in figure 2, the analysis of the quantitative criteria of 1^{st} rank represents the early stage of the detailed design and its result will be a virtual prototype (DMU). The main activities carried out at this stage are the numerical modeling of the geometry and the analysis of several candidate materials. These activities can be carried out simultaneously and they aim to analyze the product's ability to withstand the loads identified in the upstream steps. Several iterations are possible at this stage by using finite element analysis software to model the shape of the product in accordance with the design criteria of ^{1st} rank (stiffness, fatigue limit, deflection limit, etc.).

In the second step of the criteria analysis stage, designers are interested in the product's ability to respect other quantitative criteria related to the competitiveness of the product on the market such as its cost, weight or volume. These criteria are closely linked and depend on the product geometry and material choice. Backward iterations to the previous steps are also possible and even desirable in some cases to identify more relevant combinations (geometry/material) that meet all quantitative criteria (1^{st} and 2^{nd} rank).

To determine the profitability of the product the cost analysis should cover all those activities of the PDP that involve spending (design/validation, manufacturing, maintenance, recycling, transportation, storage, etc.). Thus, an inconclusive result for such an analysis could lead to stop the project or to search for alternatives (removal of a production chain, outsourcing tasks to suppliers, etc.).

Moreover, qualitative criteria analysis is imposed at the detailed design phase to verify whether a product meets the non-quantifiable requirements established at the preliminary design phase. Ergonomics, aesthetic and manufacturing are part of this category of design criteria and their analysis will provide to designers a return on customers' needs and on the conceptual choices. Thus, depending on the customer needs, several iterations may be initiated on the geometry or material of the product, always in line with the quantitative criteria analyzed in the previous steps.

As a first step of the structural validation of the product, a finite element analysis (FEA 1) is conducted using the values identified at the loads calculation step and the data regarding the characteristics of the chosen material to determine the maximum allowable stress in the critical sections of the product for a desired service life *(see the box «finite element model of the structure»* FEA 1*)*. A safety factor will be required in the case of materials for which no S/N curve is available to determine the life expectation of the product.

After determining the maximum stress that ensures the desired service life of the product, a second finite element analysis (FEA 2) is necessary to simulate the product on a testing machine and the forces to be applied by the machine. Following the finite element simulation of the product under laboratory tests conditions (FEA 2), the loads applied by the test machine should produce the same stresses in the critical sections of the product when using the service loads that were simulated in the previous step (FEA 1). By calculating the loads to be applied on the test machine, the engineers will also be able to identify the corresponding loads for a predicted service life in an accelerated test *(see the box «finite element model of the structure for laboratory tests»* FEA 2*)*.

Hence, these steps of finite element simulation represent the preliminary validation of the product (virtual dimension) and they will be followed by experimental and field tests (physical dimension), to verify the correspondence between the theoretical calculation of the product life and the results of the physical tests. The laboratory tests involve the application of cyclic loads calculated with the FEA 2 on the test machine and they are used to validate the predicted life of the product and the S/N curve of the chosen material.

Finally, the last validation of the product will be performed with the client (client validation) to ensure that its needs are fully satisfied. In this context, the client could give his opinion of the product relating to the design criteria of the manufacturer or designer, without being able to directly compare the new product with some competitor's products (in this case we are talking about an *absolute validation approach*). On the other hand, the client could also express his opinion related to competing products which are available on the market (in this case we are talking about a *relative validation approach*).

In the next section, the second design methodology based on a different design situation will be presented.

Design and Validation Methodology based on an Evolution from an Existing Product

The detailed design phase of the PDP for a new design was just formalized in the above section and several design and validation tasks were prescribed regarding the first design situation presented in the 3rd section.

Many design process are **descriptive**: they describe the elements of the design process. Our models are **prescriptive**: they prescribe what must be done during the design process. Hence, Figure 3 introduces a new prescriptive model of the design process for an evolution from an existing design (see the 3rd section). It shows the new functions of the product (sometimes identified as the requirement for a design), as the starting point. The final validation is the end point of the product design process.

When a new design is created from an existing product, it can be possible to gather and assess data about a potential design solution by undertaking experiments in the field or in a laboratory. For example, if the solution involves a structure, it may be possible to measure the stress or strength of critical parts of the design in a laboratory test (E2x or P2x).

Enough technical details have been worked out since the beginning of this stage so that it becomes possible to estimate costs, weights and overall volumes. For a new vehicle frame project, for example, the new functions to address might include the extension of a rack or a convertible top. The final evaluation of these functions will depend on the client's needs, such as the product intended use, its allowable cost, and even the client's aesthetic values.

The load cases are obtained in this instance by applying the relative approach of laboratory tests in which similar products on the market are tested. The results of these tests are used to verify or to establish a new safety factor for the improved product.

For this design situation where an existing product represents the main reference for the improved product, the design criteria analysis step will be performed following the relative design approach detailed in section 4.3 of the paper.

Unlike the first design and validation methodology presented in Figure 2, the methodology used for an evolution from an existing product (Figure3) does not require two finite element simulations because the laboratory tests performed to establish the service loads will provide enough information on critical areas of the structure. In this case, the laboratory test results combined with the product geometry and the characteristics of its material will be the input data for the *«finite element model of the structure for laboratory tests» (FEA2)* which was detailed in section 5.1. Thus, the identification of the service loads will be performed using an experimental method based upon the relative design approach.

The same approach of relative design will be used at the criteria analysis stage where the design variables such as the geometry and material will be established based on an existing product.

The design and validation methodology illustrated in Figure 3 includes appropriate physical modeling and verifications (P1x in the selection table in Figure 1) that the design requirements are met. It also includes computer modeling and simulations (N1b and N2b), prototype development (if necessary), laboratory and field tests or proof-of-concept testing (E2x). During the detailed design phase, the engineers refine and optimize the final design, assign values to variables and fix the last design details. Thus, the design process outlined in Figure 3 is not linear because two very important elements were added: feedback and iteration.

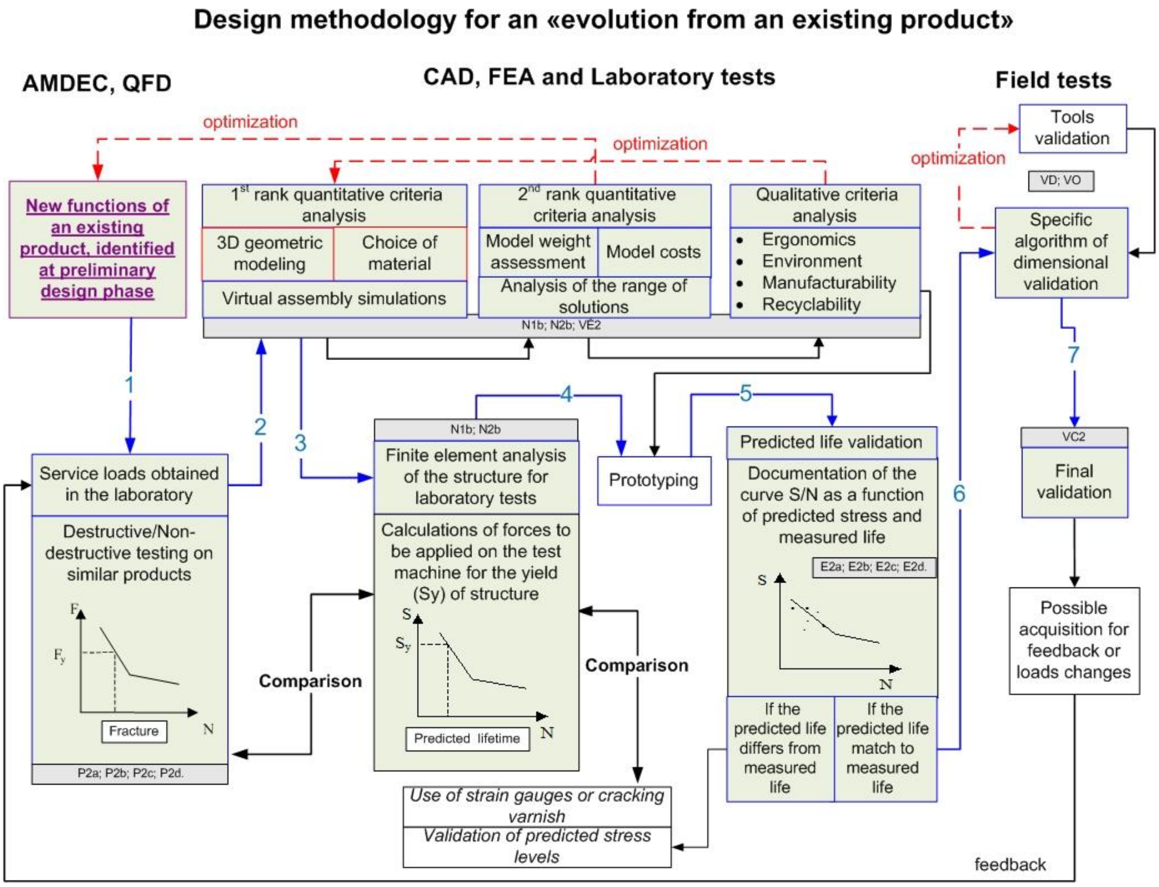

Figure 3: Generic Design and Validation Methodology based on an Evolution from an Existing Product

Feedback occurs in two notable ways in the design process: (1) First, there are *internal feedback loops* that come during the design process and in which the results of the performance test and evaluation task are fed back from the preliminary design phase to verify that the design performs as intended; (2) Second, there is an *external feedback loop* (Figure 2 and Figure 3) that comes after the design reaches its intended market and where user feedback is then exploited to validate the successful design.

The second element that was added in the proposed design methodology is *iteration*. We iterate when we repeatedly apply a common method or technique at different points of the design process. Sometimes the repeated applications occur at different levels of abstraction wherein the engineers know different degrees of detail, so they might use different scales.

Generic Design and Validation Methodology for a Variant Design Situation

The methodology shown in Figure 4 presents the flow of all the activities linked to the detailed design and validation for a variant design situation.

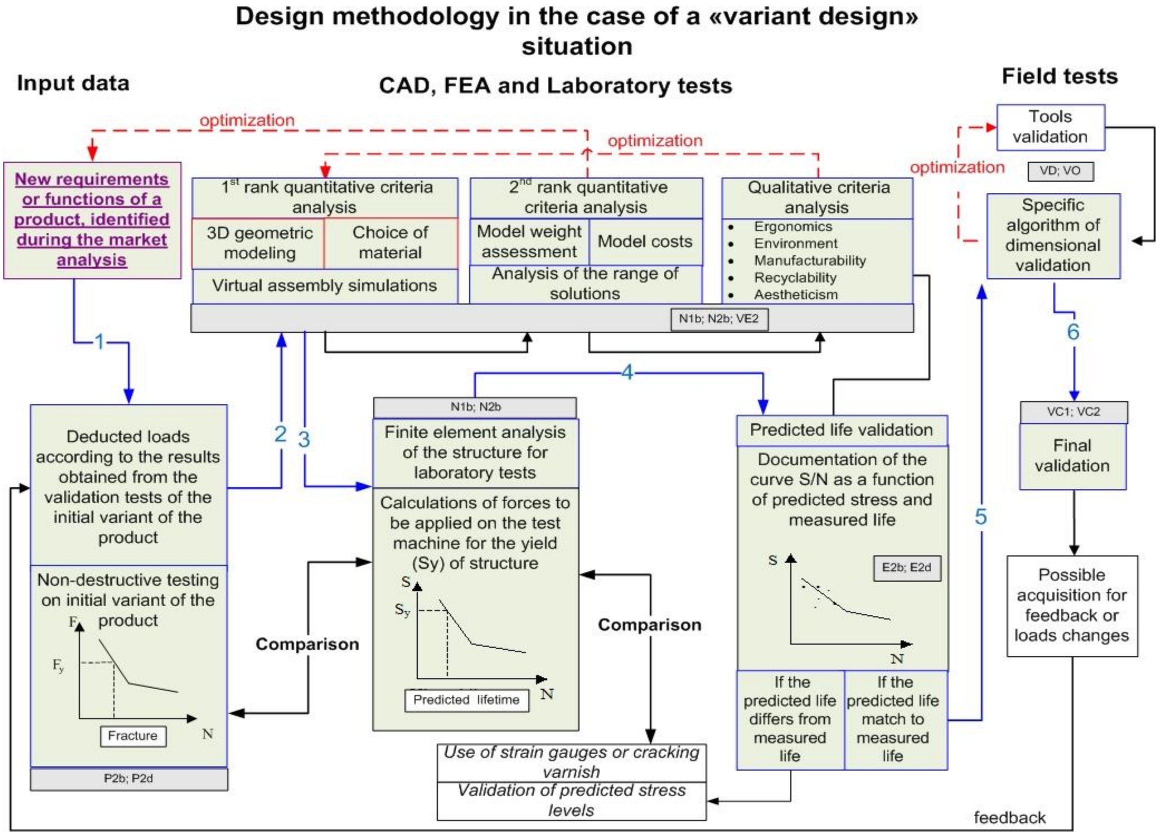

Figure 4: Generic Design and Validation Methodology based on a Variant Design

As was mentioned in the third section of this paper, the variant design usually focuses on modifying the performance of a subsystem without changing its configuration. It is implemented when scaled product variants have to be created for a product line.

For the variant design situations, the activities performed at the design criteria analysis step should not be as long as they were in the design situations presented in sections 5.1 and 5.2 because of the availability of information at this stage of the design process. In fact the concept with its embodiment already exists. The only task of the engineers at this level is to adapt the initial concept to some new characteristics and/or needs of the client.

The data obtained at the service loads identification step and those obtained at the design criteria analysis step will be used to identify the loads to be applied on the test machine (FEA2). These data have to include the three main elements mandatory in the product life analysis: loads, geometry and material. At this step, a finite element simulation will be performed with the scope of finding the loads to be applied on the test machine for an accelerated laboratory test. A comparison has to be made between the results of the simulation and those of the laboratory tests carried out to establish and validate some accelerated service load cycles applicable to the initial product. Hence, several iterations loops will be performed until the stresses obtained following both methods are similar.

The aim of the experimental validation made on the test fatigue machine is to provide the certainty that the product fulfills the quantitative criteria of 1st rank. This step of the PDP is also meant to be a very useful tool to improve or customize the existing S/N curves of the materials. The results of the experimental tests are processed and a new comparison has to be made to check the accuracy of the theoretical life prediction. At the end of the experimental validation step, the engineers may face two different situations:

- If the product life prediction doesn't mach to the measured product life, a detailed analysis of the fracture zone will be carried out by the engineers to establish whether the material properties does not correspond to its specifications or the loads applied by the test machine were not calculated properly.
- The second situation, and the most desired, is when the measured product life is the same or almost the same as the predicted life for the product. In this situation, the next activity of the PDP will be triggered by the engineers.

Depending on the product type *(structural or aesthetic)*, the first model could be built either after the criteria analysis stage or after the finite element analysis (FEA2). For example, if the engineers design an ATV headlight which is an aesthetical product, they won't need to calculate and simulate the fatigue life of the product. They will be able to build the first models of the series using just the results of the criteria analysis stage of the PDP. As it can be seen in Figures 2, 3 and 4, if the engineers deal with a structural product such as a frame or a steering arm, they will have to reserve supplementary resources (time, money, people, equipment, processes, etc.) to ensure that the initial objective of the project will be reached successfully.

The tooling validation is another very important step in the PDP. Tooling validation represent the step in which the engineers have to verify the robustness of the manufacturing process and the parameters variability during the manufacturing process. Without tooling validation, the product is not ready for mass fabrication. The risk for a company for not carrying out this step of the PDP would bear significant consequences from an economic view point not to mention its reputation. Depending on the notoriety and the resources of a company, the manufacturing process variations or in the worst scenario, its failure, could lead the company either to lose future contracts or projects or even to file for bankruptcy if the financial loss is catastrophic.

The dimensional validation step is performed with the aim to verify and validate the dimensional variations during the manufacturing process. For aesthetical products such as an ATV headlight or stoplight, this step of the PDP is critical because the gap between the product (headlight) and its vicinity (body) represent for both, the client (recreational product company) and the user (recreational product owner) two very important requirements.

For the client, this requirement is a very important specification from a product assembly point of view. For example, if the variability of the fixation points exceeds the maximal level established at the criteria analysis stage of the PDP, the fixation of the headlight on the ATV frame becomes erratic.

On the other hand, the user perception of this requirement is based in particular on the aesthetic design criteria. The user will never accept a vehicle with light fixtures that are not well framed into the body. Generally, the nominal values of these gaps and their tolerances are established by both, the designer and the client.

As well as for the first two design situations (new product and evolution from an existing product), the final validation with the client is also required for the variant design situations. At this stage of the PDP, the product is tested on the field under real service loads. Hence another data acquisition is possible either for the product feedback or for the loads validation. The final validation of the product represents the point where a design project ends and the first product series are initiated.

Conclusion

Given the fact that this paper is dedicated to the formalization and integration of design and validation activities at the detailed design phase of the design process the proposed methodologies focus on optimizing the service loads, the material and the geometry of the parts designed to be used on recreational products. Thus, in what follows, there are some elements that outline the contributions of the proposed methodologies in both academic and industrial fields of design method formalization:

- The iterative fashion of the methodologies and the integration of both design and validation activities allow the design teams to reduce the time allocated to detailed design process and to increase the accuracy of the product validation.;
- The proposed methodologies represent a very useful tool for training undergraduate students in engineering;
- The communication in the academic field will be improved by formalizing the design and validation methodologies.

From another perspective, regarding the recreational industry domain, three functions of the proposed methodologies described above have been identified:

- They provide a graphical planning tool (Workflow) for the various steps of the PDP, from the detailed design activities to the product final validation;
- They allow to combine human, material and financial resources at different stages of detailed design phase of the PDP;
- They make it easier to communicate design and validation methods among various members of the organization (managers, new engineers, technicians, etc.)

In the prescriptive design and validation methodologies presented in this paper, iteration plays a very important role in determining the material, shape and size of the developed product. This imply the initial selection of a material, shape and size for a model, with the hope that the design criteria can be met and that strength, life and safety goals will all be achieved after successive controlled improvement to the initial proposition.

Another important aspect to be taken into account by the designers is that of «design for X» where X is an attribute such as manufacturing, reliability, recycling, environment, etc. Since most products are designed to be built, sold, used and then disposed of, these attributes were collectively integrated in the proposed methodologies as qualitative design criteria.

Thus, the proposed methodologies are very helpful for the good communication among all three parties in the **designer-manager-user** triangle in which tasks such as analyzing, modeling, testing, evaluating, and optimizing are performed.

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