Abstract:

The expansion of the markets corroborated with product customization and short time to launch the product have led to new levels of competition among product development companies. To be successful in the globalization of the markets and to enable the evaluation and validation of products, companies have to develop methodologies focused on lifecycle analysis and reduction of product variation to obtain both quality and robustness of products.

This paper proposes a new design process methodology that unifies theoretical results of modeling stage and empirical findings obtained from the validation stage. The evaluations and validations of engineering design are very important and they have a high influence on product performances and their functionality, as well as on the customer perceptions.

Given that most companies maintain the confidentiality of their product development processes and that the existing literature does not provide more detailed aspects of this field, the proposed methodology will represent a technical and logistical support intended for students or engineers involved in academic as well as industrial projects.

A generic methodology will be refined based on a new approach that will take into consideration the specification types (quantitative or qualitative), the design objectives and the product types: new/improved, structural/esthetic. Hence the new generic methodology will be composed of specific product validation algorithms taking into account the above considerations. At the end of this paper, the improvements provided by the proposed methodology into the design process will be shown in the context of the engineering student capstone projects at the Université de Sherbrooke.

Keywords: Modeling, Evaluation, Validation, Design Process

1. Introduction:

The overall objective in modern product development for maximizing immediate profit can cause conflicts between business goals and engineering practices [1]. Therefore, many aspects such as ergonomics, environmental concerns, or thorough evaluation and validation are often ignored [1]. Consequently, industry demands new and adaptable methods and techniques to preserve its long-term development as well as to ensure its innovation ability to improve the product development process (PDP) [1, 2].

This paper presents the concept of integrated product modeling, product evaluation and validation into the product development process by analyzing and reviewing the field literature in: (a) product modeling, (b) digital measurement evaluation and validation, (c) virtual methods for functional
evaluation (d) cost evaluation and validation, (e) physical product evaluation and validation. The main objective is to integrate evaluation and validation as early as possible in the detailed design process, by developing new testing methods. However, the model complexity makes the realization of this integration of evaluation and validation as part of the design stages, very difficult [3, 4].

Fig. 1 illustrates the steps to be followed by the designers after the validation of the preliminary stages in the product design process. In the present industrial environment, specific methodologies are essential to deploy standardized manufacturing execution protocols in order to ensure consistent product performance in the service phase [1, 5].

2. Product modeling:

One of the principal tasks in which engineers are involved is to build a model [1]. The process of model building is a way to present know-how and to provide a geometric shape representing the best solution. Model analysis has proved helpful in product design process, particularly when experimental testing of physical prototypes is either impossible or prohibitively expensive [1, 2]. On the other hand, in experimental design the benefits of model testing are proven in several situations [3, 4]:

- When the hypothesis of the problem is too complex for an analytical resolution, an empirical approach is deployed;

- When analytical solutions can be justified only by correlating the predicted model behavior with the behavior of the prototype;

- When the characteristics of the models can’t be studied, such as those with: large structures, molecular structures or an environment that cannot be simulated.

3. Product Evaluation and Validation (E&V):

Existing validation methodologies are rarely supported by formal foundations and an efficient E&V approach should comply with the following guidelines [6, 7]:

- Enable automation as much as possible
- Encompass formal and rigorous reasoning in order to minimize human errors
- Include the graphical representation provided by CAD/CAM tools.

3.1 Virtual methods for functional product evaluation:

The finite element approach gives a piecewise approximation to the governing equations of a structure. The principle of the finite element method is that the domain can be analytically modeled or approximated by replacing it with an assemblage of discrete elements [1]. Because these elements can be put together in several ways, they can be utilized to model very complex shapes.

The company’s interest in reducing the utilization of physical tests and cutting the cost and time of product evaluation and validation has pushed the researchers toward the development of Virtual Testing Labs (VTL) where the Finite Element Analysis (FEA) technique is employed to simulate the possible behavior of real world structures before their actual failures [1, 2, and 3]. However, to replace physical testing by virtual simulations, procedures must be put in place to certificate that the virtual tests are able to replicate the physical tests and to generate the necessary confidence needed by designers [5]. The first step of the FEA is the idealization phase which takes the structural design problem and turns it into an idealized mathematical model, the Finite Element Model (FEM) [1, 5]. In the second step of the FEA the engineers have to select the appropriate finite elements: mesh layouts and solution algorithms to define the structural behavior of the idealized mechanical system [1, 5].

Even if classical computational stress analyses could provide good prediction in the elastic domain, they have not achieved yet an accurate solution in the presence of damage and fracture [5].

3.2 Product cost evaluation and validation:

The capacity to estimate costs accurately is essential if a company is to stay in business. Unfortunately, cost analysis is just an estimation process and in the best of circumstances will only provide a good approximation of the cost that will actually be engaged [1]. The cost targets of the new product should be established in the early stages of a design process [1, 2]. Thus, the system performance requirements are constantly re-evaluated to identify areas of potential cost.
reduction. The cost breakdown structure is another technique of managing cost in a major program [1]. The cost breakdown structure adapted by Ertas and Jones ties the activities of the product lifecycle to the available resources by subdividing the total cost into logical categories such as the functional areas and major tasks to be accomplish as shown in Fig. 2 [1]. The definitions used in the cost breakdown structure are adapted to the manner in which cost analysis is administrated [1].

Neglecting the time value of money, the life-cycle cost of an asset can be determined by using the equation [1]:

\[ ALCC = \frac{P}{n} + O + \frac{(n-1)M}{2} \]

...where,
ALCC=average annual life-cycle cost
O=constant annual operating cost (equal to first year operating cost including a portion of maintenance)
M=annual increase in maintenance costs
n=life of the asset in years
P=initial cost of asset

<table>
<thead>
<tr>
<th>TOTAL SYSTEM COST</th>
<th>Research &amp; Development</th>
<th>Investment</th>
<th>Operation &amp; Maintenance</th>
<th>System disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program management</td>
<td>Manufacturing engineering</td>
<td>Operation</td>
<td>Disposal of non-repairable system/ product element</td>
<td></td>
</tr>
<tr>
<td>Advanced R&amp;D</td>
<td>Tools and test equipment</td>
<td>Operating personnel</td>
<td>Maintenance personnel and support</td>
<td></td>
</tr>
<tr>
<td>Engineering design</td>
<td>Fabrication</td>
<td>Operator training</td>
<td>Spare/repair parts</td>
<td></td>
</tr>
<tr>
<td>• System engineering</td>
<td>Assembly</td>
<td>Operational facilities</td>
<td>Test and support equipment</td>
<td></td>
</tr>
<tr>
<td>• Electrical design</td>
<td>Inspection and test</td>
<td>Support and handling equipment</td>
<td>maintenance</td>
<td></td>
</tr>
<tr>
<td>• Mechanical design</td>
<td>Quality control</td>
<td>Transportation and handling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Reliability</td>
<td>Material (inventory)</td>
<td>Maintenance training</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Maintainability</td>
<td>Packing and shipping</td>
<td>Maintenance facilities</td>
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<tr>
<td>• Dependability</td>
<td>Construction</td>
<td>Documentation</td>
<td></td>
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<tr>
<td>• Availability</td>
<td>Manufacturing facilities</td>
<td>System equipment modification</td>
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<tr>
<td>• Manufacturability</td>
<td>Test facilities</td>
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<td>• Human factors</td>
<td>Operational facilities</td>
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<td>• Logistic support</td>
<td>Maintenance facilities</td>
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<tr>
<td>• Analysis</td>
<td></td>
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</table>

Fig. 2 Generic cost breakdown structure [1]

3.3 Physical product evaluation and validation:

Before virtual modeling and verification became imperative conditions of rapid product development, physical prototyping techniques were dominant in industry and have influenced product performance, quality and competitiveness in the global markets [5]. In industry practice, physical testing is still frequently linked to product certification. For example, automobile manufacturers are required to test their prototypes following combustion and safety standards [6]. However, physical tests provide important quantity of knowledge and data that can be utilized to improve the design of future products or design alternatives [5, 6].

The overall product test is pretty much defined by the V-Chart in Fig. 3. The chart contains information on the types of tests to be performed and, if we consider the X-axis as the timing, we can have a rough picture of the order in which the events take place.

Fig. 3 Engineering V-Chart [6]

A test process is complete only when training is in place to support its survival. The training has to contain the following components:

- The philosophical background of the test strategy (WHY?)
- The explanation of the test methods to be applied at the different integration levels (HOW?)
- The guidelines for applying the different test methods (WHEN?)
- A good definition of the job functions of all those involved in tests (WHO?)[6]

Hence, the following steps have to be made by the students in product durability validation to organize a service history simulation test program: 1) Test objective, 2) Test specimen, 3) Environmental input exciters, 4) Data recording Location, 5) Data analysis, 6) Test system programming and control, 7) Durability test monitoring and analysis. Each of those steps is described in detail in Ref. [6]. The challenge for the designers is to integrate these steps as much upstream as possible into the design process in order to minimize the time and costs of the PDP.

4. A new integrated design methodology at the detailed design stage:

In this section, an integration of evaluation and validation stages at the detailed design phase of the product design process will be proposed.
The goal of this chapter is to provide a good understanding and an accurate global view of the validation activities as an integrated part of the product design process. A generic framework will be developed in this section as a synthesis of the activities that should be made by the engineers regarding the design and validation criteria analysis. Several mechanical criteria will be defined as primary quantitative criteria taking into account their importance in terms of design for security. Analysis of the primary quantitative criteria will engender a calculation of safety factor for each proposed criteria. Other quantifiable criteria such as cost and weight will be considered as second quantitative criteria. They are also very important but they represent the criterions that haven’t any importance regarding the security of the product users. Moreover, qualitative criteria represent the third category of design criteria that will be taken into consideration by designers or students. These qualitative criteria will be prioritized in order to develop the matrix of relational analysis between qualitative criteria and the functional solutions according to the design variables (Fig. 4).

All design criteria defined above can also be expressed in two dimensions, depending on clients needs: absolute or relative constraints. For example a client can express a desire concerning the weight of a product component. This requirement can be absolute, when the constraint is a value that must be respected (ex.: max. 50 kg.) or relative, when the constraint is expressed as a need level of the client (ex.: the lightest in the market). Based on the approaches presented in the 2nd section and those developed in the 3rd section of this paper, a more detailed framework is proposed. The design framework developed in Fig. 5 represents an improved synthesis of all stages of the design process at the detailed design phase including the product validation stage. Depending on the product type, the proposed design framework can either be carried out in sequential or parallel format. Not all activities can be carried out in parallel due to resource constraints, product type or logical sequence of the activities.

The structured approach of concurrent engineering tools as Economic Analysis (EA), Finite Element Analysis (FEA), or Design for Assembly/Manufacturing (DFA/DFM) can ensure that future problems in manufacturing and operations can be avoided. The proposed methodology will act as a roadmap for project planning as it specifies the tools and techniques to be applied at each phase of the product design process. The methodology should also serve as a checklist to avoid omission of critical activities. The evaluation mechanism is similar to that of the stage-gate approach where all the activities are reviewed and important decisions are to be made after each review. The physical tests will then ensure that customer needs and initial design objectives are fully met. Relevant combinations of design and validation situations will be considered by engineers or students to solve problems of mechanical stress, geometry, and lifecycle. Both theoretical and experimental analysis will be imposed for each performance criterion chosen.

The algorithms developed at the Department of Mechanical Engineering of the Université de Sherbrooke are generic methodologies which involve both the virtual and physical dimensions of the design process. These methodologies were improved by integrating a criteria analysis algorithm and specific validation algorithms at the modeling stage of the product design process. The methodology shown in Fig.5 presents a generic flow of all activities linked to the mechanical analysis and validation activities of new product situations. This type of design (new design) involves the application of one or several original solutions to an arbitrary function of the product. It is however obvious for both new product and optimized design situations that the validation stages are mandatory. This aspect of product validation is imperative for both new and optimized design because the physical tests have to be made

<table>
<thead>
<tr>
<th>Criteria weighting</th>
<th>Qualitative criteria</th>
<th>Spider’s chassis (DATUM) AMS7913C/geometry1</th>
<th>Spider’s chassis AMS4209C/geometry2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weighing of model 1</td>
<td>Comment</td>
</tr>
<tr>
<td>3</td>
<td>Design for assembly</td>
<td>2</td>
<td>Reduced number of fasteners (35) and easy to assemble (1h15’)</td>
</tr>
<tr>
<td>2</td>
<td>Design for manufacturing</td>
<td>1</td>
<td>Requires welds beads in locations with limited access</td>
</tr>
<tr>
<td>2</td>
<td>Design for environment</td>
<td>2</td>
<td>Recyclable material at 95%</td>
</tr>
</tbody>
</table>

Fig. 4: Example of decision making matrix in terms of qualitative design criteria
accurately regardless of the design case and with respect to the client requirements.

Fig. 5 Integration of evaluation/validation stage in the design process for new products

To properly validate the best digital design, the results of the mechanical analysis and cost analysis must be compared to the performance criteria and the mechanical parameters established during the first stage of the methodology. Moreover, the methodology allows a comparison of results that will lead to an optimization of the geometry based on the properties of some selected materials. If the results are satisfactory after the physical tests, the product will go on to the next level of its lifecycle: manufacturing launching or process validation. If the product is not acceptable after the laboratory tests, then it becomes necessary to change its geometry and to compute the performance criteria again. The optimization loops shown in figure 5 will allow students to improve the initial design by using the feedback provided by each design analysis.

The Finite element analysis of the structure for laboratory tests represents a gate between the modeling stage and the laboratory validation of the product. This activity consists in the modeling and simulation of the testing machine in order to avoid unnecessary repeated laboratory tests. By calculating the forces to be applied by the test machine, designers will be able to predict more accurately the product reliability before the laboratory tests are performed. Therefore, the students could use this approach to reduce the optimization loops at the laboratory tests stage and to improve correlation between numerical simulation and physical tests. Thus, the designers will be able to understand the iterative overlapping in the design process and to initiate design changes between the stages early before the downstream phase begins.

Hence, the design methodology described above has been formulated to help coordinate the development phases for concurrent execution. Such an approach helps the multidisciplinary teams decide when to begin each downstream phase while reducing the iteration loops at the laboratory tests stage. Moreover, the engineering design and validation process flow developed at Fig. 5 serve as a checklist to avoid omission of certain critical
activity. Simplicity is another attribute of the framework proposed which will encourage participation and will prevent resistance amongst design team members. The generic design methodology provided in Fig. 5 illustrates the integration of validation activities upstream in product design. Up to this point, the new approach has been expressed in this paper as a set of inter-relationships between product design and validation process. The design activities flow paths have to be used in a highly interactive and iterative manner.

5. Conclusions:

The generic method of mechanical design, analysis and validation described above, could serve as a guideline for students in their decisions during the development process of their projects. Taking into account the aspects of validation activities, the students will be able to provide not only a functional design but also a reliable design in terms of lifecycle validation, with respect to project deadlines and budgets.

Sections 1, 2 and 3 review product modeling techniques (mathematical, analytical or digital) and product validation approaches (assembly and functional simulation, cost validation, physical and experimental validation), individually. The iterative fashion of the algorithm and the integration of both design and validation phases allow the students to reduce the time allocated to the detailed design process and to increase the accuracy of the product validation. The paper describes pertinent approaches in product development process and serves four functions:

1. To define what steps can be taken to achieve the initial goals of the product design;
2. To offer suggestions regarding other related things which should be examined that may give additional insight into design processes (design and validation criteria);
3. To suggest logical steps to take to ensure that additional resources and activities don’t have to be allocated to send the product to the manufacturing stage of the PDP
4. To provide students the logical and technical support needed for an improved management of the validation activities upstream at the detailed design phase.

6. Bibliography: