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A QUALITY IMPROVING METHOD TO ASSIST THE INTEGRATED PRODUCT DEVELOPMENT PROCESS

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ABSTRACT
Several studies confirm the benefits of anticipating and solving problems that might occur in a product lifecycle in the conceptual phase of the IPD - Integrated Product Development process. The challenge posed by the IPD is to develop adequate tools and procedures to make the required anticipation feasible. One problem faced by the IPD is to control the variation of the product manufacturing process that impacts directly on both product cost and delivery schedules. Corrective actions must be anticipated and carried out to reduce this variability and improve the product quality right from the beginning of the process. This paper presents the Design for Quality Costs – DFQC – a method for minimizing the non-quality costs of the new products through the anticipation of improvements in the product manufacturing process and/or product design. The proposed method is based on the concepts of Lean Engineering Thinking and DFSS - Design for Six Sigma. This paper also shows that the proposed method might be applied in the virtual environment built by Digital Manufacturing software commercially available.

Keywords: IPD – Integrated Product Development, DFSS – Design for Six Sigma, Quality Costs

1 INTRODUCTION
Many companies face quality problems with their manufactured products because they cannot achieve project specifications or keep their customers satisfied for generating defective products [1]. Many of these non-conformities could be avoided during the product design phase.
Moreover, as illustrated in Figure 1, the cost of failure increases with the number the phases of the product development process, i.e., the later the point of detection of failure the higher the cost [2].

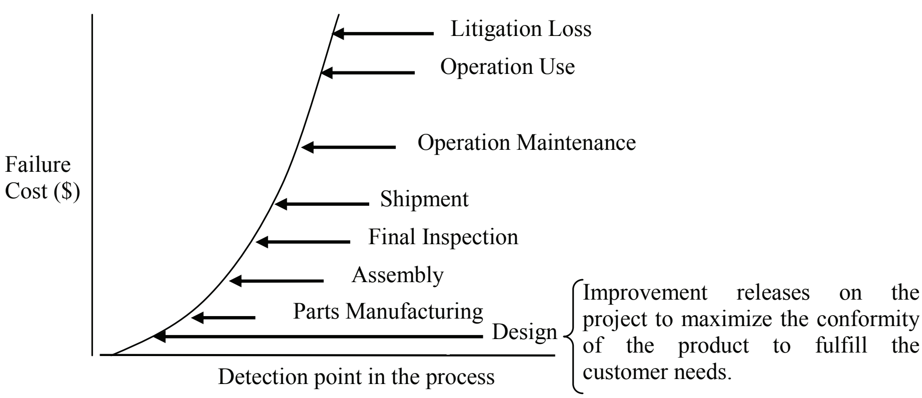

Figure 1 – Failure costs versus failure detection point [2]

Besides the cost of failures, there is a cost for evaluation (example: inspection and audit) named Quality Control cost [2].

It is also known that the accessibility for modifying the product decreases with the progression of the design phases as illustrated in Figure 2. The reason for that is: as the design process progresses the information about the product is more detailed, investments in equipment, tooling and labor have already been committed.

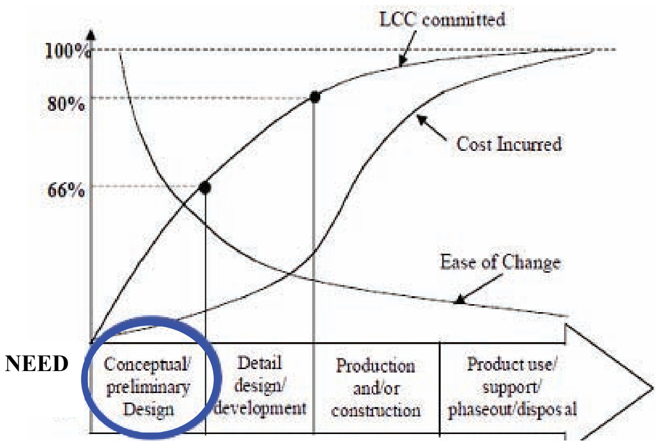

Figure 2 – Proposal of the Integrated Product Development [3]

Figures 1 and 2 summarize the problems caused by lack or improper management of information within the production development process.

A challenge for a better management of the IPD is to increase the knowledge inherent in this process. Therefore, the application of continuous improvement management has the potential to optimize the learning of these activities and consequently, the knowledge of people involved in a process [4].

Essential to this learning process is to differentiate the common causes of process variation from the special causes. This is explained by the following scenario: an organization defines its product development process with the required and optional steps. These are the necessary decisions, information flow and management standards, as well as the rules for resources allocation. When the process is in progress, significant data can be collected. The data from this process would be standardized and easily interpreted because most of its variations should be explained in the system by a common cause (e.g. drill machine change). Due to the process standardization, only the common causes of variation must be present within the data. Common causes are the sources of variation that have a routine procedure to correct them [5]. If there are special causes associated to the variations, (e.g. hardness of material out of specification) the organization must, from those data, determine and take the subsequent corrective actions. Special causes of variation generate a breakdown of routine procedures [5]. Using the process of normalization and/or statistical process control to reduce the variation of the process due to common causes, corrective actions can be taken in the standard procedures of the process. In view of this, the organization should set targets associated to each measure of performance [6]. The proposed method described herein detects the special causes from manufacturing process control data and transforms them into common causes by improvements implementation during the IPD process

A comparison between the actual metrics and the targets indicates where the organization needs to focus on and foster the learning process. This learning process should facilitate the reduction of variation process and strengthen the capacity of understanding the product development process. To reduce the variation in the manufacturing process causes positive impact on costs and deadlines due to the elimination of special causes and excessive variation in the common cause of the system. Strengthening the learning ability of people in the process generates more realistic goals and target costs; thereby it increases the probability of success in the product development process [6]. This is the main objective of the DFQC method described herein.

The method is based upon concepts of Lean Engineering Thinking and DFSS – Design for Six Sigma summarized as follows.

1.1 Lean Engineering Thinking

Lean Engineering Thinking emerged post-World War II. It has been used by the Japanese automobile industry as a fundamentally more efficient system than mass production. Lean thinking is a dynamic, knowledge-driven, and customer-focused process through which all people in a defined enterprise continuously eliminate wastes and create values [7].

The five Lean Thinking bases are stated as [7]:

1. Specify value: value is defined by customer in terms of specific products and services;
2. Identify the value stream: map out all end-to-end linked actions, processes and functions necessary for transforming inputs to outputs, to identify and eliminate waste;
3. Make value flow continuously: having eliminated waste, make the remaining value-creating steps flow;
4. Let customers pull value: customer's pull cascades all the way back to the lowest level supplier, enabling just-in-time production;
5. Pursue perfection: pursue continuous process of improvement striving for perfection.

The Lean Engineering Framework consists of eleven recommendations clustered in three topics, namely people, processes and tools. This work is focused on the topic *Adaptable tools and* subtopics: *Utilize integrated engineering tools and Design for Six Sigma (DFSS) methods, including variability reduction & key characteristics* [7].

The sub-subtopic *Design for Six Sigma (DFSS) methods, including variability reduction & key characteristics* describes the influence of quality concepts and tools during the product design phase. It is a key concept of the DFQC method.

1.2 DFSS – Design for Six Sigma

DFSS – Design for Six Sigma [8] is an approach to obtain better results in the product development process.

Design for Six Sigma is [9]:

- A methodology for designing or re-designing new products and/or processes;
- A way to implement the Six Sigma methodology in the product or service life cycle as early as possible;
- A way to exceed customer expectations and gain market share.

The Sigma Capability of a process compares the Process Voice to Customer's Voice, and it is defined as the number of Sigma between the center of a process performance measure distribution and the nearest specification limit [9].

Figure 3 illustrates the fundamental concept of Six Sigma methodology, where σ = standard deviation of a given process, LL = Lower Limit and UL = Upper Limit of product characteristic tolerance.

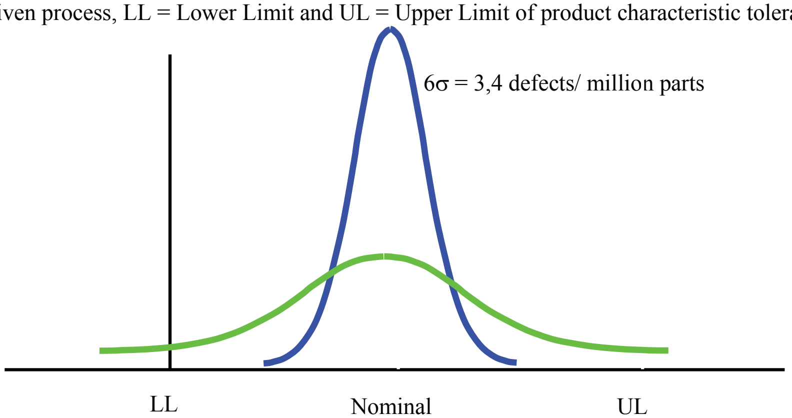

Figure 3 – Process Capability Curve – Conventional versus Six Sigma [8]

The 3σ Process is wider than the specifications, causing waste and cost of poor quality, while the 6σ Process fits well within the specifications, so even if the process shifts, the values fall well within the tolerances [9].
The concept of Six Sigma applied to processes uses the DMAIC (Define, Measure, Analyze, Implement and Control) methodology whereas the DFSS approach uses the IDOV (Identify, Design, Optimize and Validate) methodology [9].
The focus of DFQC method is on the stages "Design – Prioritized Product Design Characteristics", "Optimize – Process Capability Studies" and "Validate – Capable Product and Process" [9].
Tolerance allocation is an activity prescribed within the Optimize stage of the IDOV approach. This can be carried out by GD&T – Geometric, Dimensioning and Tolerancing analyses [10] which compare the amount of defects before and after the implantation of improvements devised in the tolerance chain. However, many manufacturing processes cannot attain the acceptable levels of capability with improvements to process only. In these cases, it is necessary to plan improvements in the product or implement conceptual design changes which are economically sound only during this stage.
The GD&T tools are based on the premise that the manufacturing process is capable. The reason for that is the difficulty in obtaining the capacity data of the process during the product development phase.
Two questions arise from that: How could the project be validated if the manufacturing processes are not able to meet the specifications? If the project is validated, how to predict the costs of failures that will occur in the following stages of the project?
The DFQC method described herein evaluates the correlation between the capability of the process and the tolerances of product (dimensional and geometric) by analyzing the financial feasibility of the implementation of improvements in order to minimize the total cost of failure in the product. This method complements the tools of DFSS and focuses the Quality Costs on the DFSS.

1.3. DFQC – Design for Quality Costs

Techniques and concepts of quality in the project, such as Key Characteristic [10], DFSS – Design for Six Sigma [8] and Costs of Quality [2] are used to ensure the total satisfaction of the customers with low cost of a product for the company. The DFQC – Design for Quality Costs method proposed in this paper is a DF (Design For) approach with emphasis on Quality Cost of Product.
Table 1 presents a comparative analysis of the concepts discussed in the literature, including the proposed method.

Table 1 – Comparative table of concepts (Adapted from [11])

Concepts/ Analysis	Traditional Engineering	IPD	DFSS	DFQC
Focus	Internal (specialist)	External (customer)	External (customer)	External (customer) and internal (manufacturing)
Style	Reactive	Preventive	Preventive	Preventive, avoid repeated failures
Executant	Person	Team	Team	Organization
Communication	Isolated	Verbal	Visual (QFD)	Visual (Financial)
Goal	Specification	Specification	Optimization	Optimization and Profitability
Innovation	Occasional, personal	Occasional (personal + team)	Systematic (personal + team)	Systematic (corporative)

Figure 4 illustrates the relationship among the concepts used within the DFQC method.

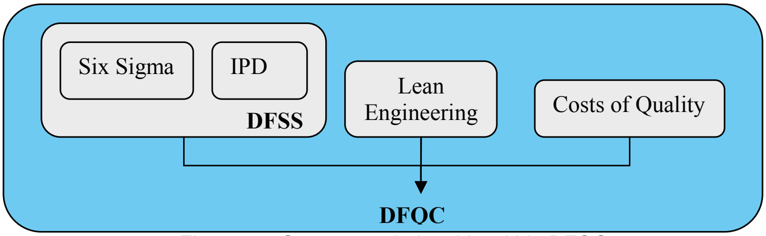

Figure 4 – Concepts relationship within DFQC

2. THE DFQC METHOD

2.1. Description

Some features of the product need to be selected and gathered as they represent customers and/or certification requirements [12]. These features are named herein KC –Key Characteristic and they are set in the product design [13]. An example of KC in the aircraft design is the gap between the fuselage skins during the junction manufacturing process.
The Key Characteristics that represent a significant risk to the successful delivery of the product as well as to impact the product's schedule and/or the cost required and/or the quality acceptance level are named STAT KC - STATistical Key Characteristics [14].
For implementation of the proposed method, two variables must be known about the STAT KC: the Tolerance values (T) and Normal Curve of the manufacturing process (μ - average, σ - standard deviation). Tolerance values (T) are attributed to KC during the product design process and Normal Curve of manufacturing process is obtained from the data of the manufacturing processes capability related to the KC. These data are usually available in SPC – Statistical Process Control [15]. If the manufacturing process is unknown, a DOE – Design of Experiments [16] simulating the manufacturing process is suggested to obtain the Normal Curve (μ,σ). If the value (T) is unknown (p. ex. a new project), a simulation of the manufacturing process using virtual manufacturing tools is suggested to analyze the tolerance value versus the manufacturing process Normal Curve (μ,σ).
Then, a comparison between the values 6σ and T is made for all the identified KC. If the T – tolerance value is higher than or equal to 6σ, this process is considered capable. Otherwise it is considered not capable, and thus, the analyzed KC is classified as STAT KC – STATistical KC.
For measuring the capability of the manufacturing process, two indicators named C_p and C_{pk} are largely applied. C_p indicates how much the sample of manufacturing process is into the upper and lower limits of tolerance. C_{pk} verifies if the manufacturing process is centralized, i.e. if the estimated μ is close to nominal value. Both C_p and C_{pk} values must be greater than 2 (6σ standard) for a capable manufacturing process. Equations 1 and 2 are used to calculate the C_p and C_{pk} values, respectively [15]:

$$C_p = \left(\frac{UL - LL}{6\sigma} \right) \tag{1}$$

$$C_{pk} = Min\left[\left(\frac{UL - \mu}{3\sigma} \right); \left(\frac{\mu - LL}{3\sigma} \right) \right] \tag{2}$$

where, UL = Upper Limit of tolerance and LL = Lower Limit of tolerance.
Whenever the process is considered capable, it is expected that the process will deliver up to 3.4 defective parts per million pieces manufactured. The DFQC method poses that the KC needs monitoring and no further action is required. For the STAT KC features however, the following course of actions must be taken.

After a STAT KC is selected, the costs of failures (rework, loss of market and so on) for each STAT KC are estimated. These costs are caused by non compliance of each STAT KC with the product.
Then the CT – total cost of failures for all STAT KC – is obtained as a summation of all individual STAT KC failures costs. The method aims at minimizing the total cost of failure of a product as indicated by Equation 3.

$$Minimize\ CT_{STAT\,KC} = C_{STAT\,KC\,1} + C_{STAT\,KC\,2} + C_{STAT\,KC\,3} + \ldots + C_{STAT\,KCn} \quad (3)$$

The proposed method evaluates the characteristics of the product using the DFSS – Design for Six Sigma [8] concept and proposes improvements by a financial comparison between the investment needed for implementing the improvements identified and the cost of failures, according to the Cost of Quality concepts [2].
The workflow of the DFQC method is presented in Figure 5. The left-hand side of the workflow represents a Design for Quality – DFQ – procedure. The right hand side contains cost procedures that might be incorporated to well establish the DTC – Design to Cost – methods.

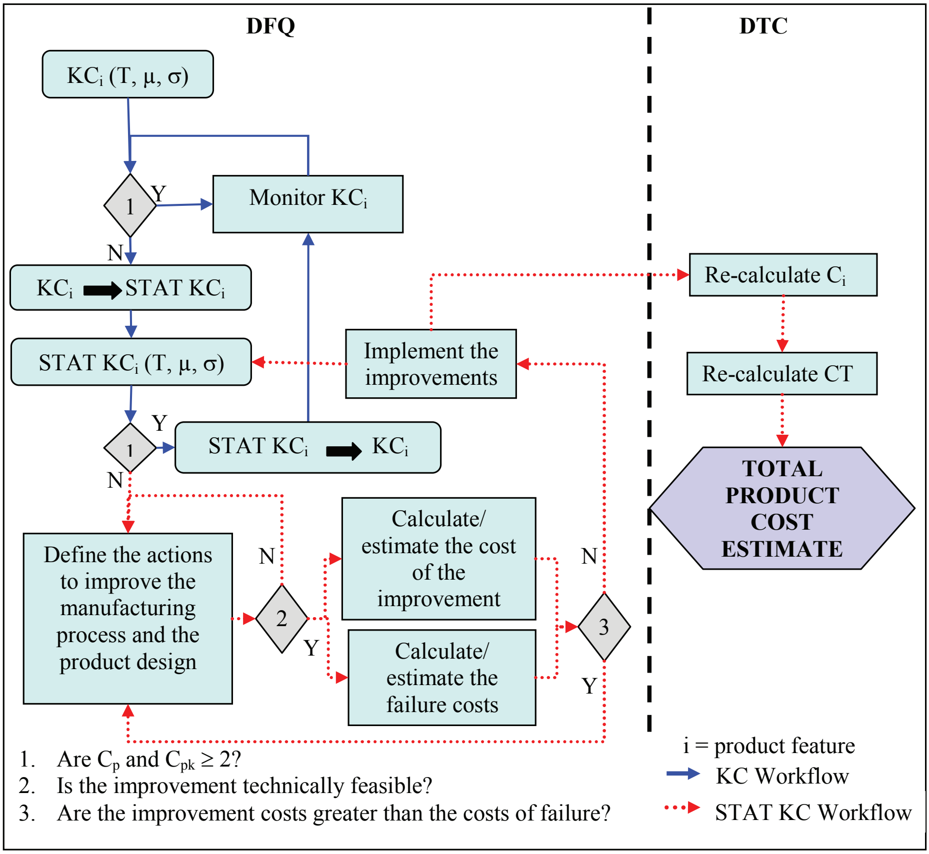

Figure 5 – Proposed method to quality improvement during the IPD

A brief description of the main steps of the workflow is given below.

- <u>Gather KC_i (T,μ,σ) information:</u> The Tolerance value (T) and Normal Curve of the manufacturing process (μ,σ) for the KC_i must be known for each KC.
- <u>Evaluate whether the Cp and Cpk are higher than 2 (6σ):</u> With the Product design (T) and the Normal Curve (μ,σ), calculate the C_p and C_{pk} values of manufacturing process. If C_p and C_{pk}

values are greater than 2, the manufacturing process is capable, otherwise it is considered unable and the KC_i is classified as a STAT KC_i.

- Monitor KC_i: If the manufacturing process is capable, this KC_i must be monitored with SPC – Statistical Process Control standard procedures.
- Update STAT KC_i (T,μ,σ) information: Tolerance design (T) and manufacturing process (μ,σ) characteristics must be updated. This step is necessary as the characteristics of the manufacturing process might change as well as the product requirements. Before the next step, it is necessary to Evaluate whether the C_p and C_{pk} is higher than 2 , as described above.
- Define the actions to improve the manufacturing process and product design: If the STAT KC_i process is classified as unable, the manufacturing process and product design are reviewed. Well established continuous improvement tools might be employed to assist this step. If the STAT KC_i process is classified as capable the STAT KC_i returns to the KC_i status.
- Evaluate whether the improvement is technically feasible: This step analyses if the improvement can be implemented without infringing any technical standard, technical functionality of the product, environmental and legal aspects.
- Calculate/ estimate the cost of improvement: After defining the improvement actions and analyzing their technical feasibility, the costs to implement each improvement are calculated or estimated if they are not readily available. The cost items might include product design changes, suppliers' qualification and monitoring, materials procurement, labor qualification, equipment purchase, building installations and so on.
- Calculate/ estimate the failure costs: the costs related to failures due to the STAT KC_i are summarized. These include: costs of rework, re-inspection, loss of market, documentation, production stops, contract penalties, transportation of materials etc. These costs are calculated for all products affected by the failure in the entire lifecycle of the product design. Whenever the costs are not readily available they can be estimated.
- Evaluate whether the improvement costs are greater than the failure costs: This step analyses if the improvement costs are financially feasible to be implemented comparing to the failure costs. If the improvement costs are higher than the failure costs, the improvement can be implemented.
- Implement the improvements: This stage consists of the complete cycle of an improvement implementation. It starts from planning, implementation schedule, team of people and areas, and the accomplishment of the improvement up to the verification of the improvement efficacy.
- Re-calculate C_i: As the improvement actions are implemented for the STAT KC_i, the failures related to these improvements are eliminated or minimized. Thus the failure cost of this STAT KC_i (C_i) must be re-calculated.
- Re-calculate CT: As the C_i is re-calculated, the total cost of failures (CT) must be re-calculated too.

The proposed method has been applied to an aircraft company, in the Horizontal Stabilizer structure drilling process. The values shown were modified for the sake of confidentiality.

2.2. An application of the DFQC method

The proposed method was applied in the Aerospace Manufacturing Process specifically in a Composite Structure Drilling process. This process was manual and did not correspond to the lead time estimated during the product development process due to large quantity of failures during the drilling process. The step-by-step procedure of the DFQC for this case is shown below:

- Gather KC_i (T,μ,σ) information: The KC_i analyzed is diameter hole of the composite structure. The Tolerance value (T) was preliminary defined by Design Engineering and the Normal Curve (μ,σ) are obtained from other products manufactured with similar manual manufacturing process, i.e. a Composite Structure Drilling process.
- Evaluate whether the C_p and C_{pk} are higher than 2: The C_p and C_{pk} of the manual process were around 0.80 and 0.65, respectively, i.e. unable for 3σ and 6σ. Therefore, this characteristic was classified as STAT KC.
- Update STAT KC_i (T,μ,σ) information: The values of tolerance design (T) and manufacturing process (μ,σ) of the characteristic were updated and the C_p and C_{pk} remain 0.80 and 0.65, respectively, because no characteristic information KC_i (T,μ,σ) had been changed.

- Define the actions to improve the manufacturing process and product design: As the STAT KC_i process is classified as unable, the manufacturing process and product design are reviewed. An improvement action plan was elaborated, and it consisted mainly of applying an automatic drilling cell to perform the holes of composite structure.
- Evaluate whether the improvement is technically feasible: A study of the automatic drilling cell concluded that the technical requirements were met by an automatic process and did not infringe any environmental or legal aspects.
- Calculate/ estimate the cost of improvement: After defining the improvement actions and analyzing their technical feasibility, the costs to implement the automatic drilling cell were calculated. The cost items included robot, equipments and software acquisition, materials procurement, labor qualification, building installations and so on.
- Calculate/ estimate the failure costs: the costs related to the failures (diameter hole out of specification) occurred due to STAT KC (composite structure drilling) were summarized. These included: costs of rework, loss of material, re-inspection, documentation, production stops, contract penalties, transportation of materials etc.
- Evaluate whether the improvement costs are higher than the costs of failure: As the product was in the Prototype Phase, hiring and qualification of labor to meet the demand have not been done, so the implementation costs of automatic process became smaller than the costs of failure, considered for the entire lifecycle of product.
- Implement the improvements: As the automatic process improvement was feasible it was implemented. After implementation of improvement, it was verified its efficacy and the C_p and C_{pk} obtained were 2.02 and 2.65 respectively, i.e. highly capable even to 6σ standard.
- Re-calculate C_i: As the new C_p and C_{pk} were capable for 6σ standard, the failures (diameter hole out of specification) was considered void, and the C_i (failure costs of this characteristic) was set to zero.
- Re-calculate CT: As the C_i is zero, the total cost of failures (CT) was also recalculated and incorporated in the Total Product Cost Estimate.

Besides the benefits described above, the lead time of automatic process decreased 50% in relation to the manual process due to the reduction of failures during the drilling process. If the quality information were not available during the IPD Phase, the automatic process could be considered unfeasible because of the manual manufacturing costs incurred in the following phases.

2.3 Advantages of the DFQC method

The proposed method examines the technical and financial feasibility of an identified improvement for both manufacturing and product design processes. It might be thought as a complement tool to the existing continuous improvement tools, such as PDCA [17].

It is worth remembering that the DFQC method has the CT – Total Cost of Failure as an output. The knowledge of such a figure contributes to mitigate the risks of several decision-making activities during the product development process that take into consideration various aspects such as: accuracy of the final product cost, financial viability, technical feasibility of the product and so on. Furthermore, the CT value might be used as input data of the product total cost estimate process.

The usage of the proposed method allows predicting the number of defects per manufactured product, to anticipate and to implement improvements in the project design and the manufacturing process to meet the product design specifications.

If the improvement actions are not feasible to be implemented during the Product Design Phase (e.g. interference in other features or requirements of the product), it is possible to plan the corrective actions of failures for minimizing their impact on the following phases: manufacturing (stock of materials, cycle time and labor) and non-conformity management process (rejection material area, MRB – Material Review Board management).

3. CONCLUSION

This paper has presented an original method for estimating the cost of failures (or non-quality) within the product development process. The method is based upon the Design for Six Sigma Method and Design for Quality concepts. It allows for a more realistic product cost estimate as the non quality costs are calculated and might be added to the traditional Design to Cost procedures.

The method has been applied to a real study from an aircraft manufacturer. The results have shown that a number of failures on the product can be avoided due to the method findings. And these failures can cause several problems such as: the great number of non-conformities, breakdown in the production line, increasing of lead time, product cost increasing and low motivation labor.
According to DoD – U.S.A. Department of Defense, "... continuous, measurable improvement should be the integral part of NPD – New Product Development implementation. Defining and using fused-process metrics allows for early feedback and continuous monitoring and management of development activities and program maturation."[17]. According to this, the proposed method might become an important tool to make product development process more efficient as far as time and costs are concerned.
This method might also be thought as being a down-to-earth Lean Engineering Thinking tool that justifies the motto "Do the right job & do the job right".

3.1. Future Developments

Further industrial applications of the DFQC method are needed to corroborate the following:
1. The use of statistical process control during IPD is more effective to reduce the variation of the process due to special causes and to take preventive and corrective actions.
2. A financial analysis of preventive and/or corrective actions prescribed by the DFQC method reduces the cost and improves the quality of a product.
3. The DFQC method focus on the organization needs and fosters the learning process of IPD process, increasing the probability of success in the project.

Other future development is to automate and to integrate the CT calculation by Virtual Manufacturing software packages available in the market. This would make possible the usage of the DFQC method during the product conceptual design phase as well as to speed up the necessary comparison procedures for all KC of a given product.

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