Lean Design For Six Sigma: an Integrated Approach to Achieving Product Reliability and Low-Cost Manufacturing.

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Abstract

The aim of this study is to discuss new product development based on a traditional stage-gate process and to examine how new product development [NPD] tools, such as lean design for Six Sigma, can accelerate the achievement of the main goals of NPD: reliable product quality, cost-effective implementation, and desired time-to-market. These new tools must be incorporated into a new approach to NPD based on the Advanced Product and Quality Planning methodology.

Key words: Design for Six Sigma, Analysis of variance (ANOVA), Industrial experimentation, Robust design, DMAIC.

Resumen

El objetivo de la presente investigación es la promoción de una discusión teórica y practica sobre el enfoque tradicional de lanzamiento de nuevos productos bajo la metodología por fases. Una revisión a profundidad cómo las nuevas herramientas del desarrollo de nuevos productos en lo particular el diseño para seis sigma puede acelerar el tiempo de respuesta al mercado de forma exitosa y a una relación atractiva de costo – beneficio. Las nuevas herramientas pueden ser incorporadas dentro de la estrategia de desarrollo de nuevos productos bajo el enfoque de planeación avanzada de la calidad de nuevos productos.

Palabras clave: Diseño para seis sigma, análisis de varianza, experimentación industrial, diseño robusto, metodología DMAIC.

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Introduction

In today's market and business environment, new product development is one of the key operations of a firm. Evolving market dynamics require new products to be innovative and competitively priced and to use sustainable technologies; meanwhile, firms require NPD to be cost-effective and to have an optimal time-to-market cycle.

NPD performance from a global perspective is most easily measured as the number of patents obtained per country and the amount of investment in R&D (research and development). (OCDE, 2012), the top ten economies in terms of the number of patents granted are almost identical to the top ten in terms of R&D investment (see Figs. 1 and 2).

Figure No. 1. New Granted Patents (OCDE, 2012).

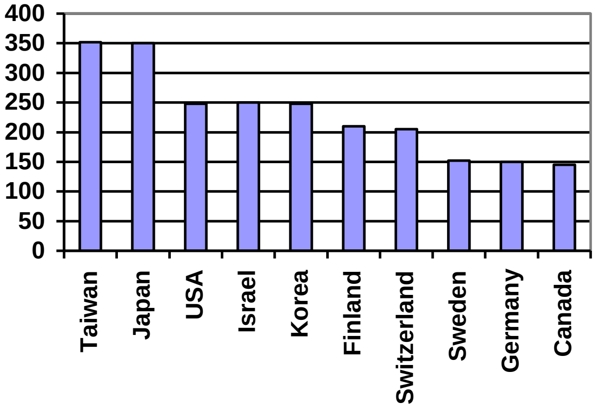
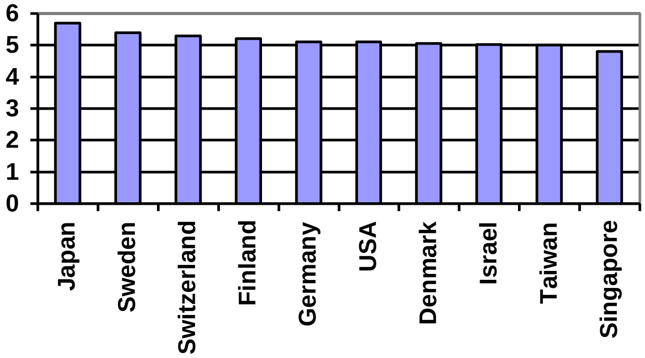


Figure No. 2. R&D Spending (OCDE, 2012).



NPD follows a traditional approach that begins with identifying a new idea or concept for a new product and continues with design, industrialization, testing, validation and sales. However, due to increasing market competitiveness, firms must incorporate advanced processes for new product development, such as APQP (advanced product quality planning) and LDFSS (Lean Design for Six Sigma).

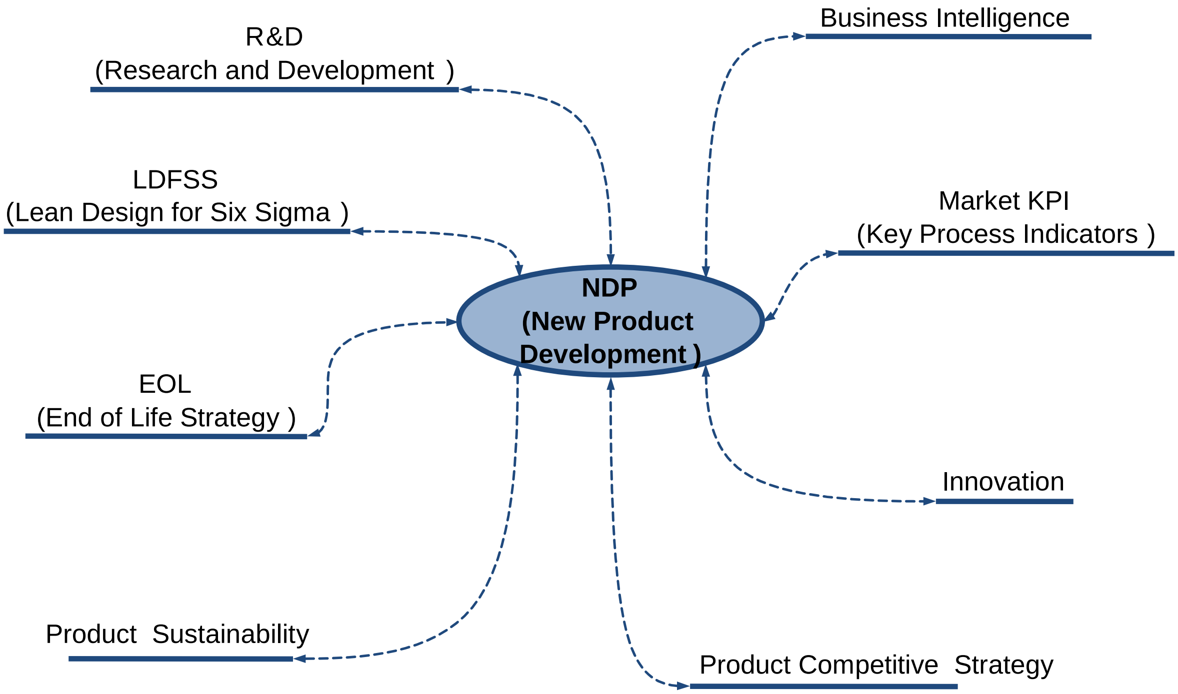
Methodology

This research paper is based on the theoretical background presented in peer-reviewed scientific research papers during the period 1990–2012. In the second section of this study, the author provides examples of the proposed tools and of advanced techniques to show evidence that validates the hypothesis.

New product development framework

In terms of its function and process, NPD represent a key strategic area for every firm. NPD is related to business intelligence; R&D, marketing, product phase in and phase out strategy, and innovation, among other capabilities (see Fig. 3).

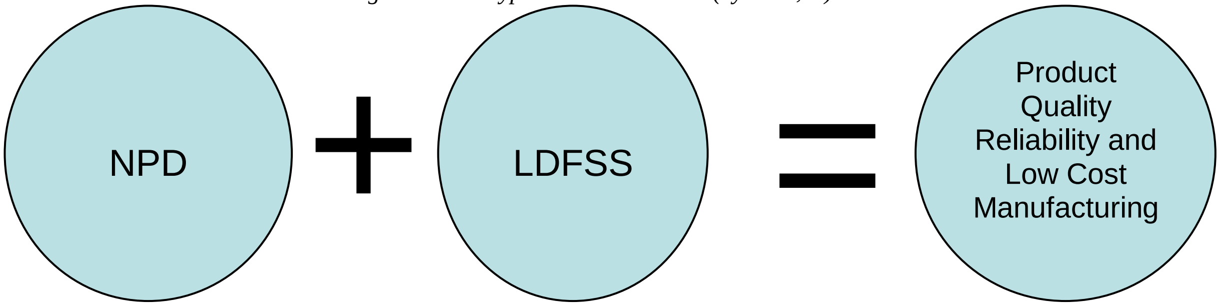
Figure No. 3. NPD Conceptual Diagram (by Cruz, J.).



Model development and hypothesis

The main goal of this study is to present practical evidence that LDFSS can be introduced into the NPD process to accelerate the achievement of its primary goals: reliable product quality and low-cost manufacturing (see Fig. 4).

Figure No. 4. Hypothesis Framework (by Cruz, J.).



Theoretical background

Some organizations have reported NPD to be one of the top three that have received the most attention, as proposed by Goetsch, D.L. and Davis, S.B. (2010), and have suggested that its success depends on design expertise and research and development capabilities in addition to the necessary input from different functional areas, as mentioned by Afonso, P., et al. (2008), Handfield, R.B., et al. (2008) and Plambeck, N. (2011). Typically, different functional areas work simultaneously during this process.

In the early stages of new product development, a cross-functional team must provide feedback on the design and help the firm to achieve a cross-validated industrial design. The key parties involved in this step include suppliers, manufacturing, and process, quality and design engineers, as discussed by Rasli Muslimen, A.S.Z.A., et al. (2012).

Communication between R&D and marketing has a highly significant effect on the final conceptual design, as does the engineers' expertise in finalizing the industrial design, as confirmed in a previous study by Chang, H.C. (2011) that examined 138 high-technology Taiwanese firms and found interaction between NPD teams. Similar theories and discussion are presented by Griffin, J. (1996), Henderson, S., et al. (2005), and Fernandez, B.I. (2001).

There are some theoretical studies that describes the relationships and business synergy associated with well-designed, customer-oriented products: Kano, N. (2001), Su, C. (2006), Fornell, C. (1987), and Cristiano, J., et al. (2000). Firms can also use web-based technology as a powerful tool that can bring them closer to customers and determine their perceptions (both positive and negative) of a product. Pioneering web-based technology focused on consumer perceptions was developed by Park, Y. (2011).

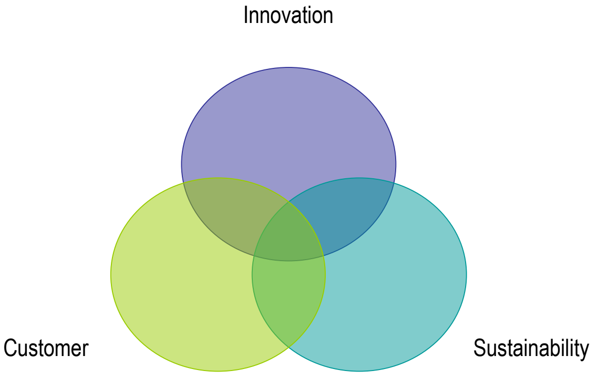
New product development requires customer input, and this knowledge can be extracted and analyzed using a variety of marketing and customer-driven tools, such as QFD (Voice of Customer and House of Quality) and customer profile studies.

New product development should be considered a powerful strategy for meeting customer preferences through customer-focused products. QFD (Quality Function Deployment) is a customer-driven approach that transforms customer expectations into engineering requirements and manufacturing process parameters. According to Pang, J., et al. [16], QFD is extremely important during the product design stage. Working papers and empirical research proving the effectiveness of QFD during a design gate include Govindalruri, S.M, Cho, B.R. (2007), Freiesleben, J. (2010) and Sharma, J.r., Rawani, A.M. (2007).

As indicated by Chan, S.L., et al. (2011), new product development includes four major steps: 1) Opportunity identification, 2) Conceptualization, 3) Product design and development, and 4) Product launch and commercialization. However, this approach is not aligned with new business dynamics (see Fig. 5). The goal of this working paper is to propose that the APQP (Advanced Product Quality Planning) methodology allows a firm to face design issues at an early stage using different tools and lean design for six sigma. This approach should make it possible to ensure better design concepts and industrialization while combining research and development with product and process reliability to create a lean product design process (see Fig. 6).

Product design and lean product design are two different concepts. Product design is a traditional approach to new product development that involves obtaining an idea, making an industrial design, validating the design and launching the product. In contrast, lean design focuses on reducing the overall product development cost and time to design as well as ensuring a cost effective product launch, as outlined by Azharul, K., et al. (2011).

Figure No. 5. Stage-Gate Process (Cooper, R.G., 2001).



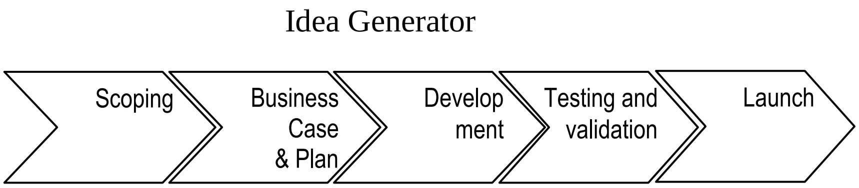
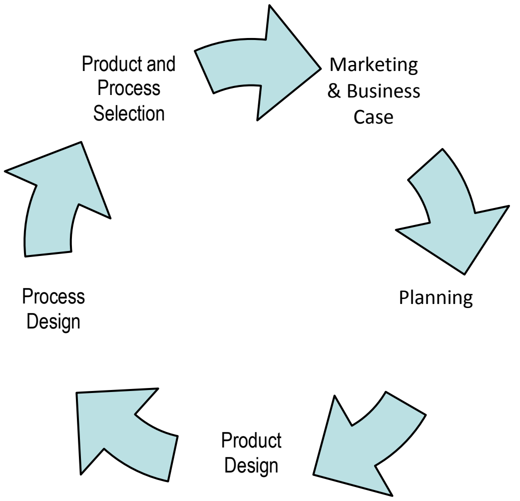


Figure No. 6. Advanced Product Quality Planning (APQP, 2007).



Previous discussions by Ulrich, K. (1995), Karim, M.A., et al. (2009), and Cloke, B. (2000) focus on the idea that organizations compete with regard to product innovation, time-to-market, and research and development. To remain on the cutting edge, companies must emphasize quality, cost, productivity and bringing the product to the market. Research and development, in addition to a focus on reliable product quality, enables lean product design development. According to Cloke, B. (2000), any type of investment made during the design stage will be lower than any type of improvement made during the product manufacturing phase.

Research and development, product quality and process reliability are not the only factors in new product development; speed to market, product quality and cost are alternative priorities. Recent empirical research by Rodriguez, P., et al. (2005) revealed that consumers are more influenced by product quality than speed to market; these results are consistent with previous research by Barker, W.E., and Sinkula, J.M. (2008), and Grinstein, A. (2005). This customer perspective demands more from organizations, which must conceptualize, design and launch high-quality products with better process manufacturing reliability than those of their competitors, according to Kirca, A. and Jayachandran, S., et al. (1995) and Atuahene, K. (2011).

According to Heinzen, M. and Höflinge, N. (2010) the competitiveness of successful firms is based on their ability to balance product quality and innovation with cost-effective NPD and reduced time-to-market cycle time. To achieve cost-effective NPD and a short time-to-market, firms must implement concurrent LPD (Lean Product Design) strategies. According to Schulze, A., et al. (2010), Womack, J., & Jones, D. (1996) and Walton, M. (1999), LPD can be understood as integrating the following steps: 1) specifying customer value; 2) identifying the value stream; 3) making the value flow; 4) letting the customer pull; and 5) ensuring continuous improvement.

Competing organizations facing these difficult business dynamics must identify their technological and human capabilities to determine and achieve key market objectives: increasing end-product quality and shortening the time-to-market cycle. Heinzen, M. and Höflinge, N. (2011) found that on-the-job training contributes significantly to the efficiency of NPD processes and enhances the motivation and skills of the new development team.

Another approach to the NPD process is explained by Grunert, K., et al. (2011), who suggested that NPD involves key process activities such as 1) consumer insight into the new product development process; 2) quality perception as a focal construct; 3) market opportunities and idea generation; 4) consumer acceptance of technology; 5) screening, concept development and concept testing; and 6) prototype testing. However, this approach does not consider process design or product and process validation to be part of an advanced focus on product quality planning.

NPD is mainly driven by cost-effective implementation and profitability. However, for optimal results, NPD must balance economics, design and ecology. The new eco-design approach impacts the overall concept of product design and the selection of manufacturing processes, as highlighted by Grunert, K., et al. (2011).

An alternative to the traditional approach to NDP that is presented by Baril, C., et al. (2011) and Breyfogle, F. (1999) employs the concept of Six Sigma as a quality philosophy that involves the use of statistical tools within a structured methodology to obtain the knowledge needed to out-compete other firms in terms of the quality, time-to-market and price of their products and services. In addition to the Six Sigma approach, Baril, C., et al. (2011) presents the key steps in the DFSS (Design for Six Sigma) process: 1) identify, 2) design, 3) optimize, and 4) validate.

Design for six sigma uses tools such as CTQ (critical to quality) analysis, GD&T (geometrical design tolerance), FEA (finite element analysis) and process design simulation to 'poke-yoke' the planned design and promote a robust manufacturing process. In addition, previous studies by Yu, J.-C. & Ishii, K. (1998), Taguchi, G. (1993), Chen, W., Wiecek, M. M., & Zhang, J. (1999), and Eggert, R. J. (1991) link the use of design for six sigma to increased product robustness.

CTQ is a common terminology that identifies a critical feature or component of quality. Once a component is defined as critical to quality, different process control activities must be conducted to ensure that the component meets the defined specifications; otherwise, the product may fail the customer.

GD&T is used to define the components' and features' required dimensions for perfect assembly; on the other hand, it also defines the allowable variation between components in terms of their linear dimensions or datum references.

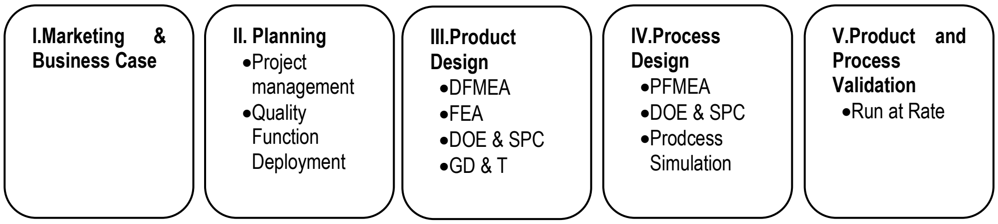
FEA is an engineering approach used to develop robust engineering products and process configurations to design to fail-free or fail-safe specifications. According to Afazov, S.M. (2012), FEA can be used to identify stressed and weakened areas and improve them accordingly based on the manufacturing process or customer use. The FEA methodology and its applications to new product development have been discussed by Pietrzyk, M., et al. (2008) and Jahansson, H. (2004).

The aim of the process design phase is to configure the manufacturing process to suit the new product design intent; as proposed by Zhenyuan, J., et al. (2011), process design can be time - and cost - effective when the organization uses special tools and techniques to develop the manufacturing process, such as the following: layout simulation, experimental design, expert systems, and the intelligent manufacturing approach, among others.

Results: LDFSS tools applied into APQP Process for NPD

Based on the theoretical background presented in the earlier section, we can focus on key elements of lean design for six sigma tools that can be introduced into the advanced product quality planning process for new product development (see Fig. 7).

Figure No. 7. Lean Design for Six Sigma Key Tool (by Cruz, J.) .



The full APQP process includes five stages or gates for the NPD process, with each step contributing to the main goal of increasing cost effectiveness and optimizing the length of the time-to-market cycle. Each step in the process includes specific tools, such as project management, quality function deployment, finite element analysis, design of experiments, and failure mode and effect analysis. The aim of this APQP case study is to present evidence of the introduction of key tools from lean design for six sigma into NPD and indicate the influence of these tools on product quality and reliability.

The following figure (see Fig. 8) contains a waterway for a commercial faucet or service sink that is composed of three main elements: a brass waterway, a water spout and an o-ring. To further analyze the potential failure modes while making the product design gate a useful tool, failure mode and effect analysis can be used (see table. 1). The FMEA process can be used in the design gate to identify the RPN (risk priority number). In this example, the failure mode that triggers an RPN 240 occurs when the system begins leaking and may experience liability issues. This, in turn, occurs when the o-ring loses compression due to its proximity to a chamfer area.

Figure No. 8. Conceptual Design of a Waterway (by Cruz, J.).

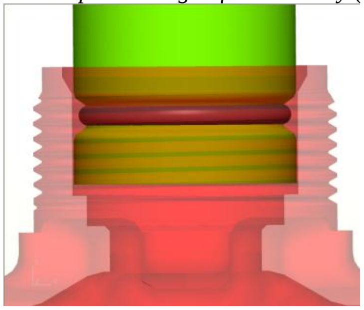


Table No. 1. Design Failure Mode and Effect Analysis.

Description	Function	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN

O-Ring groove center line too close to lead in chamfer	Waterway	Inproper o-ring compression cause leakage issue	Leakage	8	Inproper o-ring compression	10	To analyse machine process capability and evaluate poke yoke by design.	3	🟥 240

Industrial design will identify the overall dimensions of the components and the CTQ (critical-to-quality) features that may cause issues and that are related to high RPN (see Figs. 9 and 10). The CTQ characteristic for this waterway is the x-x´ dimension of the o-ring's center line and the starting point of the chamfer. This would be the location of the water leak.

Figure No. 9. Critical Dimensions Related to Industrial Design (by Cruz, J.).

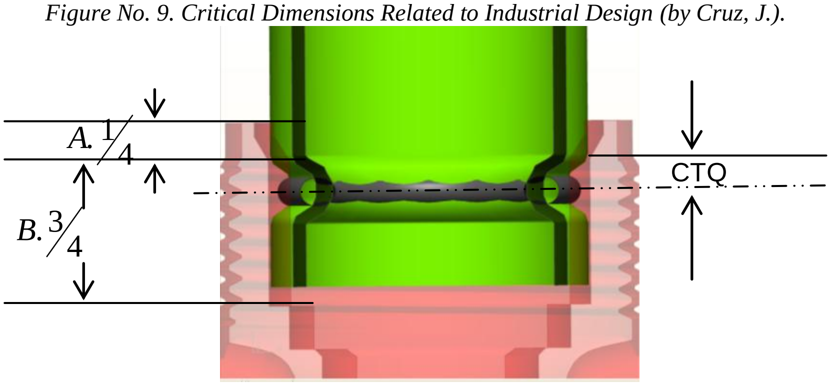
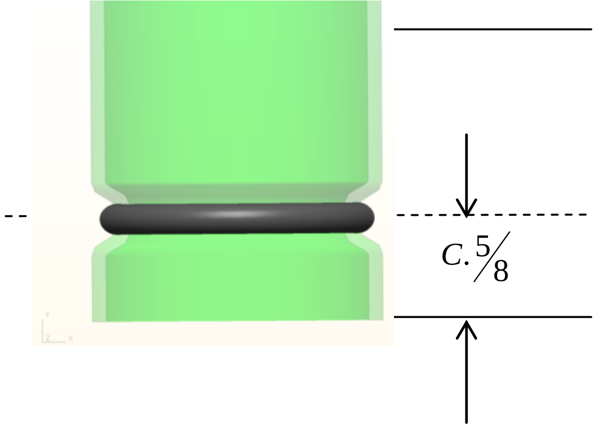


Figure No. 10. Spout Tube and O´ring Leak Free Feature (by Cruz, J.).



Industrial design based on GD&T (geometrical design and tolerance) and DFMEA can be used to determine the tolerance for each design reference (see Eq. 1). The following calculation produces the upper and lower limits for the key dimensions.

Equation No. 1. Design Specification for Key Variables A, B and C.

$A = 0.125 \, {}^{+}\!/_{-} \, 0.006.$ (nominal value) $B = 0.750 \, {}^{+}\!/_{-} \, 0.006.$ (nominal value) $C = 0.625 \, {}^{+}\!/_{-} \, 0.020.$ (nominal value)

$USL = 0.131.$ $USL = 0.756.$ $USL = 0.645.$

$LSL = 0.119.$ $LSL = 0.744.$ $LSL = 0.605.$

DOE and SPC are state-of-the-art techniques for simulating product performance through manufacturing (see fig. 11). A process capability study shows evidence of the occurrence of failure when the system begins to leak. Statistical analysis yields sufficient evidence to confirm that the key dimension "c" is at a minimum according to the probability plot analysis, and 3D software can be used to recalculate the minimum "c" (see Fig. 12). To calculate the delta, it is necessary to take the "c" mean sample value and the standard deviation (see Eq. 2) to calculate the natural upper limit and subtract from it the nominal "b" critical delta. The delta can also be shown in a normal histogram plot (see Fig. 13).

Figure No. 11. Machine Process Capability Analysis (by Cruz, J.).

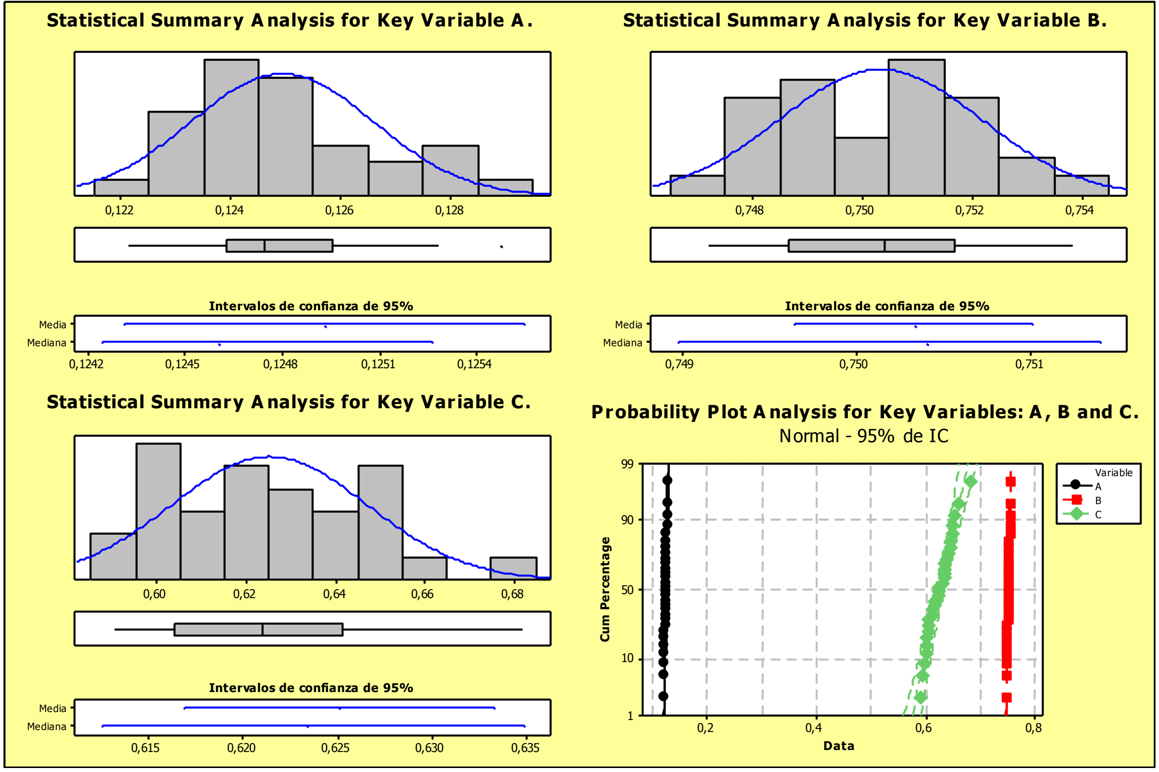
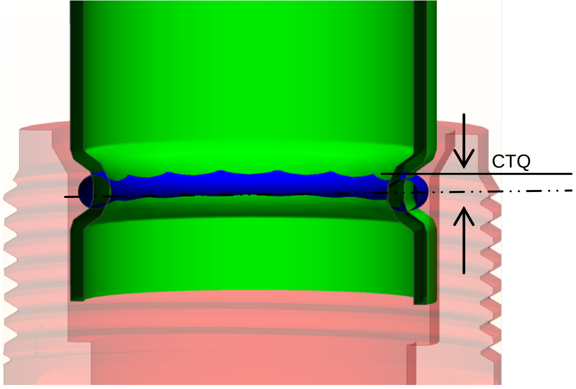


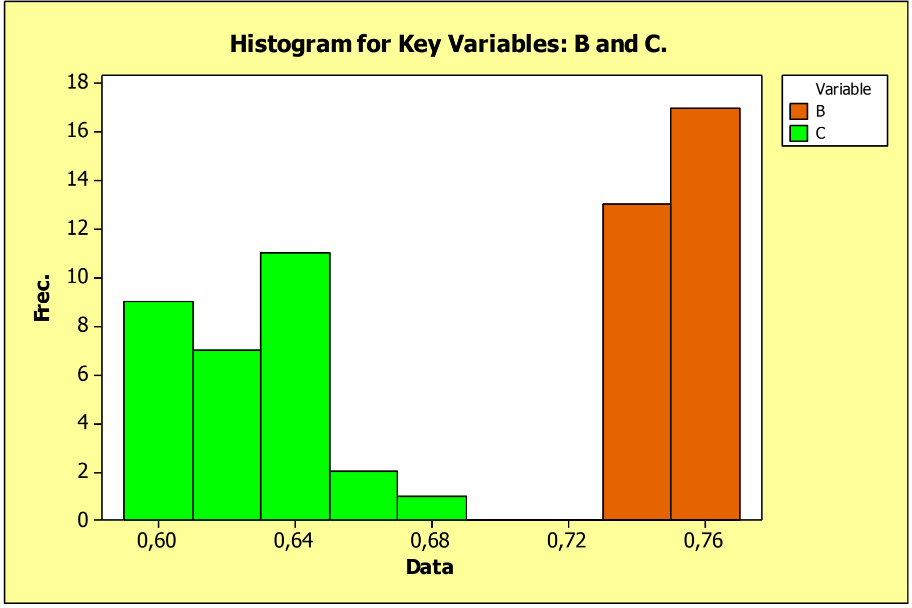
Figure No. 12. Waterway Leak Free Compromised - Failure Mode Occurrence (by Cruz, J.).



Equation No. 2. Delta Calculation to Failure Based on Upper Natural Limit.

$$UNL = 0.625 + 3(0.022) = 0.691.$$
$$\Delta = 0.750 - 0.691. = 0.059.$$

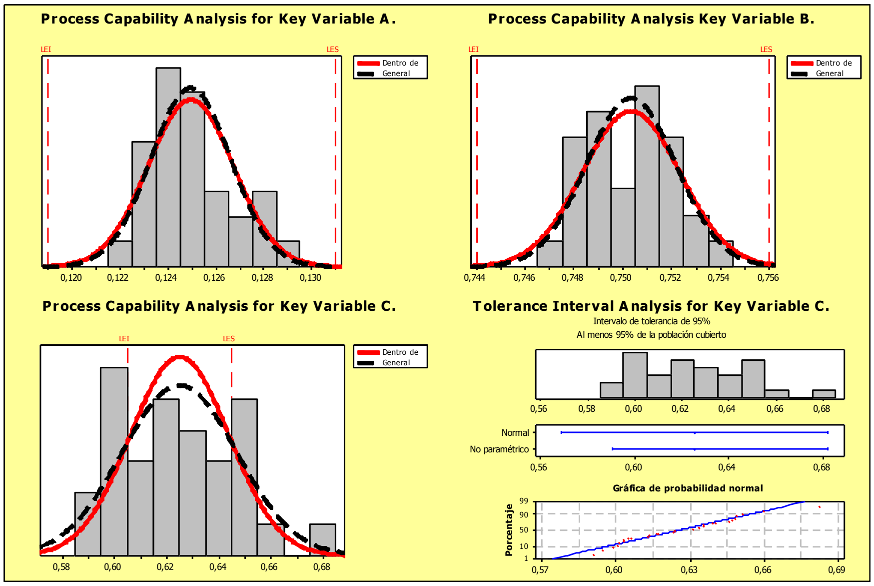
Figure No. 13. CTQ Condition Based on Random Sampling Analysis (by Cruz, J.).



Once the machine process capability is known, it can be input into a stack-up tolerance analysis to calculate the process drift in addition to a safety factor (see Fig. 14 and Eq. 3). The process drift is 1.63. sigma in addition to a safety factor of 15% to create a larger space from the upper natural limit of “c” to the lower natural limit of “b”.

This approach focuses on the downsizing strategy of RPN while reducing the opportunity of failure occurrence; following this approach, RPN decreases from 240 to 48 (see table 2). The new “c” dimension can be calculated accordingly (see Eq. 4) and theoretical new cross section of “c”. An illustrative histogram plot of the new redesigned “c” versus old “c” is shown on Fig. 16.

Figure No. 14. Tolerance Analysis for Key Dimension C (Based on CTQ condition) (by Cruz, J.).



Process Capability Analysis for Key Variable A.

Process Capability Analysis Key Variable B.

Process Capability Analysis for Key Variable C.

Tolerance Interval Analysis for Key Variable C.

Equation No. 3. Process Drift Calculation for Revised C Including Safety Factor of 15%.

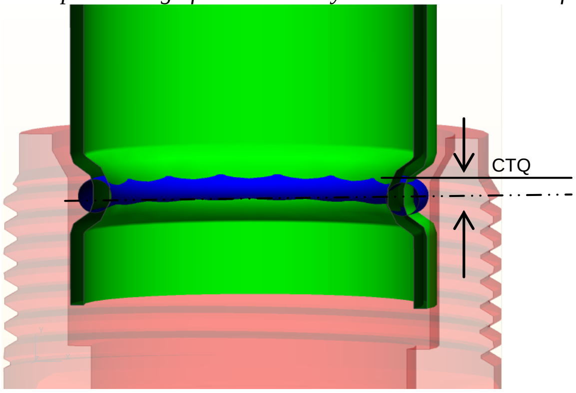
$$PD = \left(\frac{0.645 - 0.681}{0.022} \right) = 1.63\sigma.$$

$$PD^{sf15\%} = 1.63\sigma * 1.15 = 1.87\sigma.$$

Table No. 2. DFMEA Revaluation (Effect on RPN).

Actions Recommended	Resp.	Actions Taken	SEV	OCC	DET	RPN
To incorporate a safety factor on feature to eliminate the risk of failure mode	Design Eng.	Safety factor implemented	8	2	3	48

Figure No. 15. Conceptual Design for Revised Key Variable Dimension of C (by Cruz, J.).



Equation No. 4. Tolerance Design Review for C Based on CTQ Including Safety Factor.

$$C^{*} = 0.625 - 1.87\sigma$$

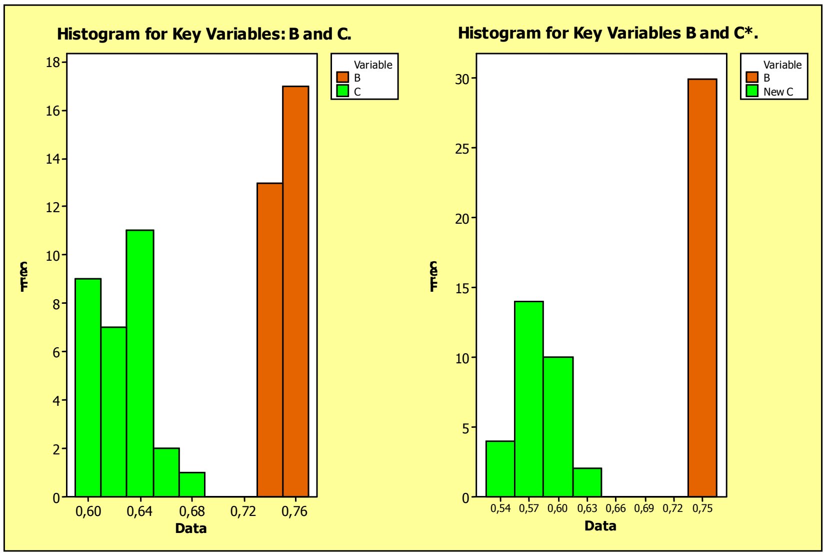
$$C^{*} = 0.625 - 1.87(0.022) = 0.583.$$

$$C^{*} = 0.583 \pm 0.02$$

$$C^{*}USL = 0.603.$$

$$C^{*}LSL = 0.563.$$

Figure No. 16. Theoretical Analysis for Revised Key Variable Dimensions of C (by Cruz, J.).



Discussion

This study presented the theoretical background on the NPD process and related functions in today's organizations as it relates to competition. NPD was identified as one of the top priorities of every firm, which is why the NPD process must be optimized and oriented toward customers to ensure the quality and reliability of products while minimizing manufacturing costs. To fully deploy all NPD tools requires basic steps such as the following: marketing and planning, design, process, product process validation and the integration of operations from a concurrent engineering standpoint.

Lean design tools can easily be introduced into the advanced product quality planning process to ensure the implementation of cost-effective new product development processes intended to ensure product and process reliability and minimize failure during the design stage. This approach will significantly impact goals regarding product quality and reliability and customer expectations.

The effect on timing and cost is greatly appreciated by top management, and it is well known throughout the firm when a strong, reliable product is launched that it is flawless. All departments involved in the introduction of new products are aligned with the top priorities: 1) safe launch, 2) reliable product quality, 3) timing, and 4) budget. Although these four priorities appear to be opposing, they that must be met concurrently to ensure a successful NPD launch.

The case study presents a typical, straightforward design. Even when the design and development stages are complete, there is are opportunities for improvement when the new product enters the manufacturing process, as it is possible to address the potential for failure due to leaks. This case study shows the application of the traditional stage-gate process, which employs a very basic concept of a safe NPD launch, but not the application of the advanced product quality planning framework, which aims for a flawless and cost-effective NPD launch.

The NPD tool kit integrates DFMEA, CTQ, FEA, DOE, and simulation, among others, which are used in the advanced product quality planning framework. In the case study, the RPN decreased from 240 to 48. Although the potential for failure remains, the occurrence of failure was reduced to a parts per million measure in the single digits, which indicated that excellence in manufacturing and reliable product quality had been achieved in addition to low-cost manufacturing. The tools work, and the knowledge is there; top management must simply support the use of this approach to ensure successful NPD launches. Using this approach will earn firms high recognition among end consumers due to their product quality and readiness for manufacturing.

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