Smart Design and Manufacturing of Power Transformers Tanks

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***Abstract*—Industry is undergoing through noteworthy changes, where most of the methodologies and procedures are increasingly assisted by advanced information systems. In addition, the communications between the entire product chain have been progressively more effective, allowing to support better decisions in the early phases of the product development. This industrial change demands companies to rethink the planning, design and manufacturing phases, so as to take advantage of these developments. This article addresses an empirical assessment based on the Design for eXcellence (DfX) concepts aiming a smarter design and manufacturing of fully customized power transformers. Several design for excellence disciplines are discussed and analysed considering a specific case study, where the transformer tank geometry was changed. The resulting consequences in the final product can be systematized analysing the overall product lifecycle. Inputs to the product development through these design disciplines have the capability to identify advantages, disadvantages and improvement opportunities. Furthermore, the accumulated knowledge and the consideration of these approaches in a continuous improvement action will allow the enhancement of the efficiency and reliability throughout the design and production cycle of a power transformer.**

***Index Terms*—Power Transformers, Design for X, Design for Excellence, Product Development, Product Life Cycle**

I. Introduction

In customized, large-scale and complex products, the conceptualization, budgeting and design phases of the product lifecycle management represent a significant effort, cost and risk due to the presumed assumptions, requirements balances and available lead time. These phases limit the ability to provide a faster and more accurate response to the demands of a customer. Therefore, organizational and functional solutions that streamline the entire design and production cycle are extremely valuable in this type of products. In order to follow the market trends and increase competitiveness, several projects have begun to reorganize the methodologies in practice. The aim is to find the best trade-off between cost-quality-time, regarding the planning, design and manufacturing phases.

The product development of complex systems includes many different interactions between diverse stakeholders. Most approaches for product development systematization might be reduced to a four stage-gate framework: *(i)* concept development; *(ii)* design; *(iii)* validation and *(iv)* in-service product support, [1]. As the product complexity increases more phases and/or stages are added for a more rigorous control. Typically, a more detailed second stage framework, related to the design (and development), will reduce the effort required in the third stage and the respective risks. Diverse tools and methodologies for product development have been developed in multiple contexts. For instance, Lutters et al., in [2], details the common techniques for structuring the product development process and improve the decision making.

From the technical point of view, the product development, and more specifically its design, may also be highly multidisciplinary, demanding the combination of different requirements and complex engineering characteristics during the whole lifecycle. In these cases, Complex Adaptive System (CAS), or equivalent frameworks are employed aiming to disaggregate the development and to improve the decision making, either at a specific stage, at revision level or even, at strategic level, [3].

Concurrent Engineering (CE) or integrated product development is one of the common methodologies adopted to improve the productivity and the time-to-market during the product development. Multiple studies demonstrate the advantages of this methodology application during the product development. Koufteros et al., [4] evaluated statistically concurrent engineering practices in 244 firms, showing that the ones that employ these practices are the ones that have better performance in product innovation and quality, and improve their ability to charge premium prices. Al-Ashaab et al., in [5], present a set-based concurrent engineering approach using lean principles, to improve the product development processes. This approach is focused on the product value, on the set-based solutions, on the integrated documentation, on the knowledge creation and on the innovation, resulting in better available alternative solutions, higher level of innovation and decreased risk of rework.

Several software tools, supporting the application of concurrent engineering approaches and the systematization of product development, are available. The most known, from the industrial point of view, are the Product Lifecycle Management (PLM) solutions which enable the integration of people, information and processes linked to the product and

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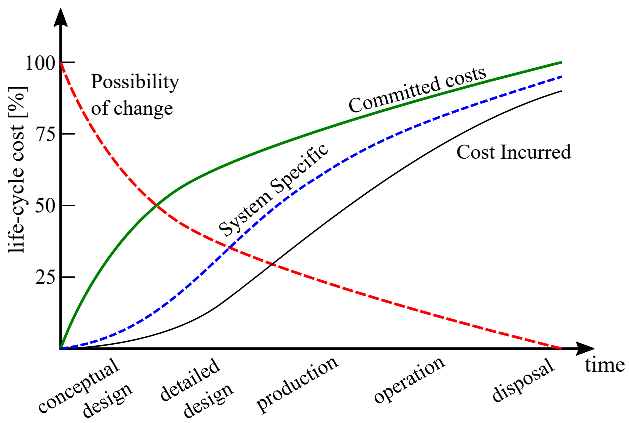


Fig. 1: Lifecycle costs committed and incurred, and the effect of system specific knowledge approaches (adapted from [8] and [9]).

through the enterprise, in a common and real-time accessible source, [6]. The product lifecycle management approaches have been exploited in different perspectives, including the product–process integrated design using system modelling language, [7].

Multiple works and much research have been carried out with these methodologies so as to improve the design and development practised in different sectors, the quality control and reducing overall product costs, [8]. The relevance of these is evidenced by the fact that the final product cost will be essentially defined during the initial design phases, Fig. 1. Therefore, the right decisions must be taken at the earliest stages of the product development cycle, while changes at advanced stages must be avoided. As for Westinghouse, late changes have large impacts on both the final cost, product quality and lead time, [9].

During the design phase, system analysis with a holistic perspective will be able to prevent a high commitment of costs. From the industrial perspective, the typical approaches with potential impact are the Design for eXcellence (DfX) disciplines (also known as Design for X, where X stands for a specific discipline). Immediate considered disciplines are the design for manufacturing and design for assembly (also known as DFMA) since those have a clear impact on the production of the product, [10]. However, considering the product lifecycle, other disciplines should be included aiming to improve the product in different dimensions during the early stages of the product development, [11].

In this article, a power transformer tank is used as case study, though its conventional geometry has suffered some modifications aiming a multi-objective optimization. The impact in the lifecycle of a power transformer (which can be higher than 40 years) is evaluated considering multiple disciplines of the design for excellence. In the following sections, the tank geometry is detailed and each design discipline is concisely analysed.

II. Power transformers

Power transformers are static electrical machines able to convert an input voltage level into another output voltage level, by means of electromagnetic induction. This product has different functional designs, depending on the voltage level, range of application, construction (Core or Shell type) and rated power. Transformers closer to the generation plant are usually large power transformers whereas distribution transformers, used to distribute the electrical energy to the consumers, are smaller in size. Distribution transformers typically have power ratings up to 2.5 MVA whereas power transformers have ratings from 2.5 MVA up to above 1000 MVA.

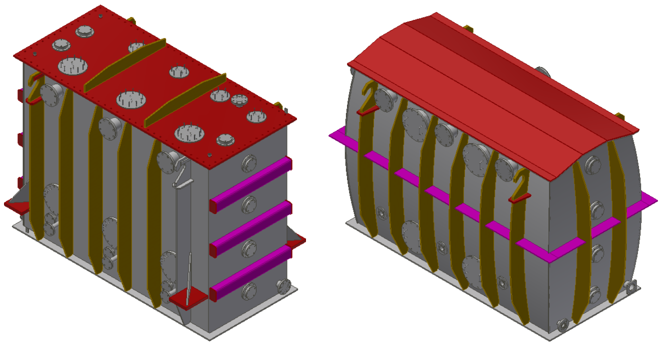
These machines have very conservative designs with only incremental changes during the last decades. For high power rates and special applications, these transformers have a high degree of customization, requiring dedicated designs from electromagnetic and structural point of views. Therefore, each product requires a dedicated product development process, taking into account all the customer requirements.

Commonly, the design process of a power transformer is divided in the electromagnetic design, structural design and thermal design, related to the major expertise areas. In the last years, transformers acoustic design have been imposed by the utilities to aim low noise levels, specially in the major worldwide cities. Concurrent engineering between these areas is intrinsic to the product development process, through diverse specialized tools. Most of the design communication is carry out by technical drawings, which are also used for manufacturing, assembly, transportation, installation and maintenance. Design for Excellence was considered in an informal and an unsystematic manners in the past, however it has been increasingly covering more and more disciplines in systematic design revisions.

III. Case Study

Power transformers are continuously re-engineered to reduce costs through optimization of the different parts through new materials and new geometries aiming mass savings and reduced lifecycle costs. This case study addresses the structural design of a core type oil immersed power transformer, mainly composed by a reinforced tank. The tank must support multiple loading conditions and during its lifecycle must hold the oil without leakage even during discrete events, as internal arcs, short-circuits or seismic events. The tanks such as those shown in Fig. 2 may have a length ranging from 3 m to 8 m, a width of 1.5 m to 3 m, and a height of 2 m to 3.5 m. Their mass may reach 80 ton, the tank itself consisting about 10 ton.

Currently, conventional tanks are designed with a prismatic shape and straight horizontal and vertical reinforcements (stiffeners), as shown in Fig. 2a. This stiffening approach allows to increase the wall bending strength with limited impact on total weight, ensuring that the tank withstands pressure loadings imposed since the manufacturing stage up to its use. However, other geometrical configurations, besides the conventional planar one and particularly ones which increase the stiffness of the tank, have been explored aiming to improve the specific behaviour under different conditions. Increasing the stiffness of the tank can be achieved through an innovative shape, more stable and lightweight with the same or higher capacity to accommodate the different loading scenarios. Manufacturing and transportation costs reduction are also foreseen in most of conditions. As shown in Fig. 2b, the key design changes in the proposed improved power transformer tank consist in the use of curved reinforced steel panels and stiffeners obtained from single steel sheets. This enhanced design is the result of various iterations and optimization procedures being refined based on the final product specifications.



(a) Conventional tank (b) Curved walls tank

Fig. 2: Examples of transformer tank geometries.

A. *Design for Excellence considerations*

Considering the comprehensiveness of requirements and specifications of the different stakeholders related to the transformer structural parts, the design for excellence can be addressed in diverse dimensions. From the structural point of view, one of the most relevant aspects on the mechanical design of the tank, obtained by welded construction, is to reduce total weight while maximizing stiffness and keeping the specific structural strength. This case study analyses different design disciplines, usually discussed in Design for eXcellence (DfX) initiatives, which have impact in the final product and during its lifecycle. In addition, the major differences are discussed considering the conventional tank and the curved walls tank geometries. The Design for eXcellence (DfX) disciplines considered in this study were:

- Design for Assembly
- Design for Manufacturing
- Design for Safety
- Design for Noise Reduction
- Design for Maintenance
- Design for Test
- Design for Quality
- Design for Reliability
- Design for Recycling
- Design for Reuse
- Design for Transportation
- Design for Costing

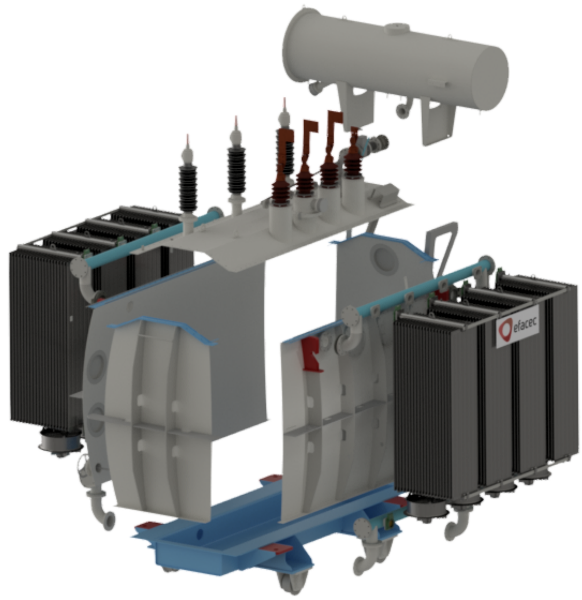


Fig. 3: Power transformer structure, without active part - exploded view.

Fig. 3 shows the major structural parts of the new transformer tank configuration. These parts are assembled and joined by welding processes or bolted joints.

1) Design for Assembly: In the case of power transformers structures, several methodologies are used to meet the design for assembly. An immediate breakdown is the placement of strategic features in the reinforcements of the tank, allowing to prepare the cable pathway in later phases of the project. Another case is the execution of sheet thickness reductions whenever possible. Taking into account the simplification of the reinforcements in curved design, it was possible to estimate the optimum areas for cable pathways and optimize the reinforcements positions and dimensions. Additionally, the joining processes between components are improved, reducing the number of welded joints and the number of interceptions between welding lines.

Another frequent procedure in the design of the welded construction of the transformers is the definition of specific locations so that the connection of the accessories and external equipment is directly connected to the tank. The goal is to avoid additional components such as collars, flanges and pipelines.

2) Design for Manufacturing: The design for manufacturing can be defined according to Bralla, [12] as "primarily a knowledge-based technique that invokes a series of guidelines, principles, recommendations or rules of thumb for designing a product so that is easy to make". In this context and for the power transformer tank represented in Fig. 3, it is possible to identify several manufacturing advantages and drawbacks: *(i)* horizontal and vertical reinforcements that are obtained by high speed cutting process, as laser beam cutting.

With this solution the base structure of the tank (walls and reinforcements) can be obtained exclusively from steel plates, reducing manufacturing lead times; *(ii)* side panels have the lower edge bended, allowing to avoid cross welding in the connection between side panels and bottom part, increasing the level of manufacturability; *(iii)* the side panels require a plate rolling machine to generate their curvature radius, so the time for manufacturing is increased relatively to a flat panels; *(iv)* manholes, holes for accessories, piping and other components of the transformer tank are standard to keep high manufacturability and reduced lead times. Additionally, with this standardization a stock is kept to lower the time of the manufacturing process; *(v)* bended tank cover requires the bending operation machine and diagonal cutting of components (as manholes), which results in higher manufacturing time than a planar configuration; *(vi)* a 3D CAD model, nowadays with product and manufacturing information (PMI), is delivered for manufacturing, allowing any indefiniteness to quickly clarified, and so reducing the manufacturing lead time.

3) Design for Safety: The design for safety approach considers the health and safety of any parties involved, in all stages of a products lifecycle, as the top priority. This means that any potential hazard or risk of injury that may occur (whether it is for the worker, the transportation, the maintenance or the costumer) needs to be either eliminated, which would be the ideal outcome, or minimised as much as possible. The curved design of the panels in the new tank configuration can be considered safer when compared to the standard one since the structure has more flexibility, being able to withstand greater deformations and so, decreasing failure risk by, e.g., oil leakage. In both manufacturing and disposal phases, to handle curved panels safely, new set-ups were prepared. However, considering their higher specific strength, the safety concerns are slightly reduced due to lower mass for the same transformer characteristics.

4) Design for Noise Reduction: The design for noise reduction in power transformers aims the mitigation of the radiated noise level. To achieve this objective, it is essential to identify *(i)* sources of vibration and noise, as well as, *(ii)* the main transmission paths and, *(iii)* to reduce the transmission and radiation efficiency of the power transformer.

The vibration generated within the active part of the power transformers is transmitted through either fluid-structure or structural-structural interactions. Therefore, the oil is responsible for a part of the vibration transmission in a power transformer; the other part is transmitted through structural connections between components. The curved tank design retains more oil around areas of the active part with larger vibration amplitude, contributing therefore to an enhanced vibroacoustic response of the power transformer.

Besides the transmission efficiency, and as depicted in Fig. 4, one of the parameters that most affects how the structural vibration velocity (v) is converted to acoustic power (W) is the radiation efficiency (σ), [13]. Indeed, the radiation efficiency can be used as a metric of the transformer design from the acoustic point of view [14]. Besides the vibration

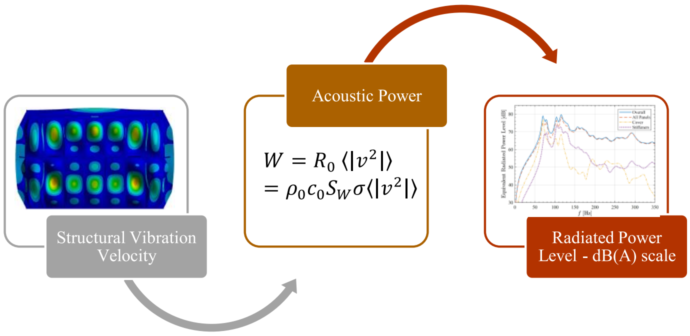


Fig. 4: Major steps in the analysis of a power transformer radiated power level, [14].

frequency dependency, the radiation efficiency is also affected by the geometry and structural properties of the transformer components.

5) Design for Maintenance: To improve the maintenance of a power transformer during its service/operation, the design for maintainability must be fully implemented during its design. As regards to the innovative transformer tank, all critical components where periodic maintenance is required (such as the transformer tank, top oil thermometers, winding temperature thermometers, oil level indicators, pressure relief devices, sudden pressure relay, Buchholz relay, transformer bushings, oil preservation sealing systems, among others), were designed and assembled with the purpose of being easily accessible during preventive or corrective maintenance actions. In addition, on the transformer tank, several decisions have been made about components that directly or indirectly influence the transformer maintenance. For instance, by looking at Fig. 3, the panels were bent at the bottom. One of the reasons why this steel plate is bent, besides avoiding interrupted weld beads and the lower probability of oil leakages from the bottom of the transformer tank, it that maintenance is easier to be implemented.

6) Design for Test: The life of a product can be divided in four different stages, namely pre-life, early life, useful life and wear out. In each stage failure can occur, and different considerations to avoid this should be taken. During pre-life the main objective is planning and design. The design has the greatest impact on its reliability. Considering the transformer tank, the major risk is related to oil volume changes during normal working conditions, environmental stress, corrosion, high humidity and sun radiation, possible creating some cracks that will induce leakages. These leakages will reduce the level of oil in the tank, leading to less insulation. Oil is also used for cooling purposes, therefore oil reduction leads to overheating. Structural weld beads subjected to stresses should be carefully inspected. Currently, only visual and liquid penetrant inspection is performed, although some non-destructive techniques may be used either during manufacturing or working life such as radiographic and ultrasonic inspection. These methods would allow an automatic procedure to inspect weldments. It is also seen that the tank has some components where the sealing is critical such as: flanges; inlet and outlet piping and cable passageways. The sealing in these parts is made using gaskets, nuts and bolts. The nuts and bolts used to tension gaskets and flanges should be properly tightened and calibrated using a torque wrench. Pressure tests before and after filling should be done as well as vacuum and vacuum leakage rate test which is only achieved if the transformer is properly sealed.

7) Design for Quality: The level of quality of a product can be considered as a result of the satisfaction that the customer presents after a certain time of use of the product, taking into account several factors such as ease of access and maintenance, security or for example the operating costs. In global terms there are several aspects that are taken into account during the design of our product that fall under this philosophy, such as: *(i)* the use of qualified, detailed and specific welding specification procedures for each welded connection; *(ii)* the traceability of the material used in the welded construction and its mechanical tests used in specific components, guaranteeing the quality of the material, *(iii)* destructive tests and non-destructive tests *(iv)* the use of standard components in the tank wherever possible and *(v)* specific dimensional control essential to the operation of the product (internal dimensions and positioning of the pins of the magnetic circuit). All these aspects are in line with some product quality guidelines proposed by Bralla in [15].

8) Design for Reliability: Design for reliability in structures has been connected to fatigue loading conditions due to their effect on the material strength behaviour and the consequences on the global structure reliability. However, in quasi-static loaded structures, this concept can be exploited during all lifecycle and considering the bath curve of the failure rate of a system, considering all types of failure modes, giving assurance that the structure will withstand all types of loads with a high percentage of confidence, including the less unexpected loads, [16]. In the case of power transformers tanks, design for reliability takes into account discrete loading conditions, including: tank transportation; assembly; vacuum; lifting; transformer transportation; installation with hydraulic jacks; hydrostatic pressure; service loads; seismic events; etc. Most of these loads are quantified with a significant degree of confidence. In current case study, improving the geometry of the tank allows to increase the reliability of the transformer, without significant impact in the cost.

9) Design for Recycling: Materials conservation concerns require that a recycling strategy at the end-of-life (EOL) must be taken into consideration at design stage, so as to: *(i)* improve the rates of recovery of materials at the EOL; *(ii)* assure that each and every material, and substance, undergo a correct and safe procedure; and *(iii)* minimum economic penalties are attained. Given that the power transformers can be commissioned on remote locations, and that transportation activities intrinsically hold some associated risks, and are somehow complex and costly activities, an eventual EOL take back strategy is likely unpractical in most cases. Therefore, the recommended approach is rather to: *(i)* design the product for an easy material identification, for simplified dismantling, and

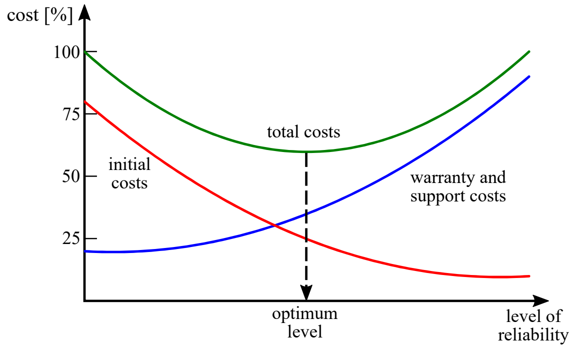


Fig. 5: Design for reliability impact, adapted from [17].

reduce the total number of different materials employed; *(ii)* avoid or minimize the toxicity of materials and substances involved; *(iii)* reduce the environmental impacts of the materials used, from a cradle-to-grave perspective; *(iv)* inform the client on the best available options at EOL for each material and substance; *(v)* support the clients on decommissioning pathways, namely by proactively seeking local partnerships, capable of performing adequate and economic recycling activities.

10) Design for Reuse: The reuse strategy, by way of refurbishment or remanufacturing, brings about a number of known economic and environmental benefits [18]. Power transformers reconditioning/remanufacturing for reuse, are highly challenging for many reasons, and decision-making process on one such possibility should be carefully considered, given that: *(i)* remanufacturing is mostly performed on high-value products, and that remanufactured products retain only a fraction of the original value, normally representing about 60-70% less value [19]; *(ii)* although environmentally and economically sound, the large scale availability of remanufactured units would, in theory, slightly erode the market demand for new units; *(iii)* geographical dispersion of commissioned units and the transportation endeavour, which relates to size and weight, among others, challenge the rational for take-back strategies aiming an eventual refurbishment; *(iv)* given that power transformers are often designed for specific client requirements and working conditions, it is harder to refurbish them as needed by the marketplace (this problem is likely alleviated if commissioning on the exact same application is needed). Altogether however, societies and organizations highly value positive contributions to the circular economy, and perceptions on that are on the rise, by way of recycling, reuse, remanufacturing and other alike strategies. One detrimental factor impacting the widespread adoption of such strategies is the poor design for manufacturability and assembly/disassembly. With the foregoing in mind, the power transformer has been designed for long lifespans, while some features were introduced that facilitate eventual disassembly operations.

11) Design for Transportation: The delivery of power transformers to the commissioned sites, requires challenging handle and transportation activities. These challenges relate to the abnormal weight and size of the cargo, which might exceed the binding standards for normal circulation on public roads, [20], thus requiring complex and highly specific transportation means and procedures. IEEEC57.150-2012 standard is commonly used as a reference guide for governing the safe transportation of power transformers [21]. The overall transportation cost can be broadly indexed to the weight of the power transformer. Its tank, in turn, is one of the foremost components contributing to its total weight. Therefore, one possible approach, to simplify the transportation activity and reduce costs, is to optimize the design of this component, aiming the reduction of its dimensions and weight. This can be done by introducing new materials and designs, and by using novel calculi methodologies [22], and advanced dimensioning criteria, e.g. grounded on the thorough deployment and validation of the elastoplastic behaviour of the materials, under a number of extreme situations.

12) Design for Costing: Design for costing (DfC) is one of the known cost management techniques, described as a systematic approach for the control of a products cost ever since its early stages of conception. By taking right decisions from early on, and through a real-time supply-chain data to assess design choices with cost objectives in mind, unnecessary costs at later stages can be avoided. This approach needs to consider manufacturing lead times, volume pricing, volume capacity, logistics, and other relevant information. In design for cost there is not a target value for the cost of a product, it is rather about "considering cost as a design parameter in product development activities". In the case of transformer tanks, the manufacturing lead times have been reduced through the number of manufacturing process variants. For instance, in steel plate cutting, the number of sheet thicknesses and structural profiles have been reduced with impact in the number of process changes during the tank fabrication, resulting in significant cost savings.

IV. Conclusion

Considering the conventional product development process of customized and large-scale power transformers, decisions taken during the design phase are critical for the product success and with consequences to the all product lifecycle. Therefore, efforts for improvement the design phase have an increasing importance in recent years, taking into account the application of new methods, as the concurrent engineering and design for excellence approaches.

This article exploits diverse design for excellence disciplines aiming to improve the transformer structural design. For this analysis, a case study composed by a conventional tank and an innovative tank was considered. Different design for excellence disciplines were analysed with the objective to improve the product design. This study established advantages and drawbacks due to a design change, allowing a more comprehensive scrutiny of the impact in the product lifecycle.

From this analysis, the curved walls tank design demonstrates several advantages in different design disciplines, due to the mass reduction, parts simplification and accessories arrangement. The impact in the transformer lifecycle is considerable, improving the overall solution performance. Addressing continuously the design for excellence disciplines allows to prevail advantages during the product life.

References

[1] R. Phillips, K. Neailey, and T. Broughton, "A comparative study of six stage-gate approaches to product development," *Integrated Manufacturing Systems*, vol. 10, no. 5, pp. 289–297, 1999.

[2] E. Lutters, F. J. van Houten, A. Bernard, E. Mermoz, and C. S. Schutte, "Tools and techniques for product design," *CIRP Annals-Manufacturing Technology*, vol. 63, no. 2, pp. 607–630, 2014.

[3] I. P. McCarthy, C. Tsinopoulos, P. Allen, and C. Rose-Anderssen, "New product development as a complex adaptive system of decisions," *Journal of Product Innovation Management*, vol. 23, no. 5, pp. 437–456, 2006.

[4] X. Koufteros, M. Vonderembse, and W. Doll, "Concurrent engineering and its consequences," *Journal of Operations Management*, vol. 19, no. 1, pp. 97–115, 2001.

[5] A. Al-Ashaab, M. Golob, U. M. Attia, M. Khan, J. Parsons, A. Andino, A. Perez, P. Guzman, A. Onecha, S. Kesavamoorthy *et al.*, "The transformation of product development process into lean environment using set-based concurrent engineering: A case study from an aerospace industry," *Concurrent Engineering*, vol. 21, no. 4, pp. 268–285, 2013.

[6] F. Ameri and D. Dutta, "Product lifecycle management: closing the knowledge loops," *Computer-Aided Design and Applications*, vol. 2, no. 5, pp. 577–590, 2005.

[7] F. Demoly, D. Monticolo, B. Eynard, L. Rivest, and S. Gomes, "Multiple viewpoint modelling framework enabling integrated product–process design," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 4, no. 4, pp. 269–280, 2010.

[8] S. Chen and L. K. Keys, "A cost analysis model for heavy equipment," *Computers & Industrial Engineering*, vol. 56, no. 4, pp. 1276–1288, 2009.

[9] B. S. Blanchard and W. J. Fabrycky, *Systems engineering and analysis*, 4th ed. Prentice Hall International Series, 1990.

[10] M.-C. Chiu and G. E. O. Kremer, "Investigation of the applicability of design for X tools during design concept evolution: a literature review," *International Journal of Product Development*, vol. 13, no. 2, pp. 132–167, 2011.

[11] U. Dombrowski, S. Schmidt, and K. Schmidtchen, "Analysis and integration of design for X approaches in lean design as basis for a lifecycle optimized product design," *Procedia CIRP*, vol. 15, pp. 385–390, 2014.

[12] J. G. Bralla, *Design for Excellence*. McGraw-Hill, 1996.

[13] C. Coutinho, C. Novais, S. Tavares, M. Pinto, A. Vieira, C. Linhares, H. Mendes, and R. C. Lopes, "Dynamic response of power transformer tanks," in *9th Power Instrumentation and Measurement Meeting, IEEE EPIM*, 2018.

[14] M. Kozupa and K. Kolber, "Radiation efficiency as a crucial parameter in transformer noise evaluation," in *Forum Acusticum*, Krakow, Poland, September 7-12 2014.

[15] T.-C. Kuo, S. H. Huang, and H.-C. Zhang, "Design for manufacture and design for 'X': concepts, applications, and perspectives," *Computers & Industrial Engineering*, vol. 41, no. 3, pp. 241–260, 2001.

[16] D. Crowe and A. Feinberg, *Design for reliability*. CRC press, 2001.

[17] D. Kececioglu, "A blueprint for implementing: A comprehensive reliability engineering program," *HBM Prenscia Inc.*, 2016.

[18] F. Moreira, "A step forward on cleaner production: Remanufacturing and interchangeability," in *4th Ed. of the International Conference on Wastes: Solutions, Treatments and Opportunities*, Vilarinho, Castro, and Lopes, Eds. Porto, Portugal: CRC Press, 2017, pp. 197–202.

[19] M. A. Ilgin and S. M. Gupta, *Remanufacturing modeling and analysis*. CRC Press, 2016.

[20] P. Hoffman and W. Bryan, "Large power transformers and the US electric grid," DOE/OE/ISER Report of US Department of Energy, Tech. Rep., 2014.

[21] K. Budin, "Transport, installation and commissioning of power transformers," *Transformers Magazine*, vol. 2, no. 1, pp. 22–29, 2015.

[22] C. Linhares, V. Carneiro, J. Meireles, A. Pinho, and H. Mendes, "Main frame structural optimization for power transformers in short circuit," in *Innovation, Engineering and Entrepreneurship. HELIX 2018. Lecture Notes in Electrical Engineering*, J. Machado, F. Soares, and G. Veiga, Eds., vol. 505. Springer, 2018, pp. 478–486.