Multidimensional Evaluation of Production Systems Design Based on Design-for-eXcellence Methodologies

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Abstract. To address the increasing complexity of product characteristics, demand fluctuations, and higher costs of raw materials, along with pressures for fast-er integration of decarbonized energy resources, manufacturing companies require flexible production systems. These systems should minimize waste, achieve faster cycle times, and deliver high-quality products to stay competitive. In this regard, Product Design-for-Excellence (DfX) principles have gained significant importance in recent years. DfX enables all management levels to perform quick and comprehensive design inputs and performance evaluations, leveraging product lifecycle management platforms. LeanDfX, a dedicated Lean approach for product development performance assessment, has been previously proposed. This work builds upon LeanDfX by presenting a multi-dimensional approach to support design and performance assessment of production systems throughout its lifecycle. This approach coherently integrates different production knowledge areas and strategic foundations (e.g., Lean Manufacturing, Strategic Aspects, Sustainability, and Circular Economy) for the effectiveness and efficiency evaluation of production systems. The research hypothesis revolves around the translational strategy of extending and transforming the LeanDfX methodology for application in production system design within factory operations. This new architecture is presented in the context of the European project RENÉE, devoted to designing and deploying remanufacturing processes for a more sustainable, circular, and competitive industry.

Keywords: Production Systems Design · Performance Assessment · LeanDfX · Circular Economy · Remanufacturing

1 Introduction

In response to dynamic market conditions influenced by evolving customer demands and advancements in technology, companies are compelled to guarantee swift responsiveness to stay competitive [1]. In light of market volatility and the shift in power towards customers, driven by the abundance and diversification of solutions in products and services, it is imperative for companies to continuously assess their competitiveness [2].

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The escalating demand for accelerated production times, enhanced product flexibility, competitive pricing, and innovation, all while upholding standards of quality and reliability, has placed substantial pressure on manufacturers. [1, 2] There is a high pressure that companies face for less usage of resources but keeping or improving, the current state of products. [3, 4] Analyzing data from all dimensions helps organizations optimize performance and allocate funds towards value-added activities by identifying waste and non-value-added areas. [5].

Design for Excellence, or in its similarity acronym "DfX", was first proposed by Bralla in 1996. [6] It offers versatile design approaches that emphasize optimization upstream, at the design stage, rather than downstream, during the production stage, as compared to previous methodologies. DfX optimizes product performance while meeting specific requirements, leading to increased profitability. [7] Some of the most common DfX methodologies in literature are: Design for Assembly (DfA) [8], Design for Manufacture (DfM) [9], Design for Disassembly (DfD) [10], Design for the Environment (DfE) [11], Design for Sustainability (DfS)[12], and Design for Quality (DfQ) [13]. Despite the relevance of DfX and Design-for-eXcellence methodologies, few researchers have explored using multiple DFX to optimize product life cycle from a more holistic perspective to easily develop new methods. [14].

Focusing on the product design, process design, manufacturing and operations, Wild et al. developed a spreadsheet to estimate unit cost, inventory level, and response time. [15] Other researchers focused their studies on integrating the system into the scope of product optimization, by incorporating Axiomatic Design into the manufacturing methodologies. [16] Ming-Chuan et al. proposed a categorization of DfX tools by dividing a factory into three domains: product, system, and ecosystem. [17] Some of the benefits of incorporating DfX methods studied by Venkatachalam et al., that highlights the financial and operational gains by implementation of these methods. [18].

By merging Lean thinking to DfX approaches, LeanDfX (Lean Design-for-X) was developed in the past decade, that studies the product in higher detail, adopting a modular design approach, defining X "domains" and assessing performance for multiple design key performance indicators. [6] Primarily focusing on the entire lifecycle of the product, LeanDfX evaluates diverse design requirements and product specifications in a systematic and "X" dimension based. By breaking down the product, there is an insight look at each system-module-(…)-component effectiveness and efficiency [6].

While the potential of Design for Excellence (DfX) methodologies is recognized, there is a notable scarcity in efforts to establish cross-links between the product development knowledge base and respective subsets of production systems design. Regarding the appliance of DfX tools to the entire production system lifecycle there were found some barriers by Bastas. [19] In that work, it was emphasized the necessity for the development of DfX tools that consider the "triple bottom line" of sustainability throughout the entire product lifecycle (economic, social, and environmental). It suggests that an organization's success and impact should be measured not only by its financial performance (profit) but also by its social responsibility (people) and environmental stewardship (planet). Additionally, the researcher underscored the significance of enhancements in data management and advocated for broader research efforts beyond the automotive and machinery sectors. Other limitations were found regarding the lack of interest of the current state of engineering solutions [20], the need for supporting tools to make the procedure of system configuration more efficient, reducing process time, and more effective, so increasing the chance to design the best configuration. Other.

This paper proposes a novel approach to address the above cited gaps, either for the LeanDfX methodologies current limitations of not attend to the production systems specificities and factory operations-oriented nature, but also the opportunity to study the suitability potential of adopting DfX approaches of X multi-dimensional design within the context of production systems. The work was framed in the European Project funded RENÉE project, that intends to achieve sustainable remanufacturing operations in the context of enabling circular value chains with cross-sectoral applicability.

The manuscript is organized as follows. Firstly, the introduction frames the research topic and literature gaps within the context of complex production systems design and the parallelism of functional performance assessment of complex product development. Secondly, Sect. 2 describes the research strategy conducted in the development of the novel approach starting on LeanDfX framework. In Sect. 3 the conceptual architecture is parameterized regarding the multi-dimensional "X" dimensions envisioned into RENEE's project remanufacturing focus applications. Finally, in Sect. 4, the main conclusions and findings are presented, the limitations of the present approach, and future paths of development.

2 Fundamentals and Methodology Development

2.1 Research Development Strategy

To develop the new method for evaluating the performance of production systems, the first step was to explore the functional design limits of LeanDfX framework by extending its applicability. Thus, first, it is considered that a given production system acts as a sum of multiple mechanic or mechatronic products, thus machines that transform raw materials or work-in-process into components, and auxiliary equipment for inspection stages, conveyers, etc. (Eq. 1)

$$ProductionSystem = \sum Machine(i) + AuxiliaryEquipment(j) \quad (1)$$

The base analysis proposed covers the functional aspects of the production system, as a sum of the functionalities required for each production system process step, materialized as a product, either be a machine or an auxiliary equipment (excluding auxiliary factory systems as HAVAC, Compressed Air Systems, Boilers, etc.). Therefore, the Total Performance of the production system would be represented as a sum of the performance of each "LeanDfX machine" assessment plus "LeanDfX Auxiliary Equipment" assessment. Although functional design and modularity can be shared on performance assessment of either product and production machines, a given production system design contains other order aspects that LeanDfX and complex product development does not cover and must be integrated into the envisioned new framework model. Therefore, it was considered a consecutive integration of factory management aspects, such as, the paradigms of sustainability and circular economy, strategic vision, operational management, that converge into the functional and modular approach o LeanDfX complex products and operational management of production systems assessment. The main research question addressed in this research is: How traditional LeanDfX can be applied/transformed to design assessment of production systems and in the context of circular economy and remanufacturing processes.

2.2 LeanDfX Methodology

The original LeanDfX analyses different "X" dimensions of a product lifecycle. The product is studied regarding its effectiveness and efficiency in the following steps [6]:

1. Modularization: for deeper performance analysis, the bill of materials zooms into product components, enabling study of complex systems through submodule decomposition.
2. Selection of Design Domains and Indicators: through multidimensional DfX analysis, considering product goals and key "X" dimensions.
3. Calculation of the ratios of effectiveness and efficiency: the calculation is presented in the percentage format. The assessment of performance for each submodule is followed by an aggregation of results in a "bottom-up" sequence.
4. Analysis of results: the usage of scorecards makes the summarized results of the "X" domains performance easy to interpret at all levels of management. The evaluation is marked by four different colors (green, orange, yellow, red).
5. Improvement of the design: in the continuous and iterative process of refining design and addressing ineffective outcomes, the iterative stage involves enhancing modules that have variables in their most critical state.

2.3 Product to Production System Transition Assessment

Figure 1 outlines the proposed conceptual architecture for the approach. The initial challenge consists in what modifications must LeanDfX methodology encompass, by expansion, for the transition from product design into production system design support. The first finding consists in retaining all principles of LeanDfX, and above cited pillars, but integrating fundamental aspects of strategic vision and operational management in the context of a factory.

Strategic vision and operation optimization can, for instance, be addressed by state of art approaches such as Lean Manufacturing. Indeed, Lean Production represents a cornerstone on production systems management, for strategic top-down vision, and organization constructive feedback action, for waste reduction and continuous improvement, following eight principles: standardization, zero defects, flow, pull, continuous improvement, employee orientation and management by objectives, visual management and avoidance of waste [21, 22]. Furthermore, the production system analysis should encompass essential components such as production planning, logistics, workforce, finances, and others. These dimensions, while distinct from the physical machinery, must be integrated into the overall production processes management. Consequently, an initial study of the production system's hierarchical structure is crucial to understand how to modularize it effectively, drawing on insights from product studies and it is important to systematically relate the production system performance and its multidimensionality of knowledge areas.

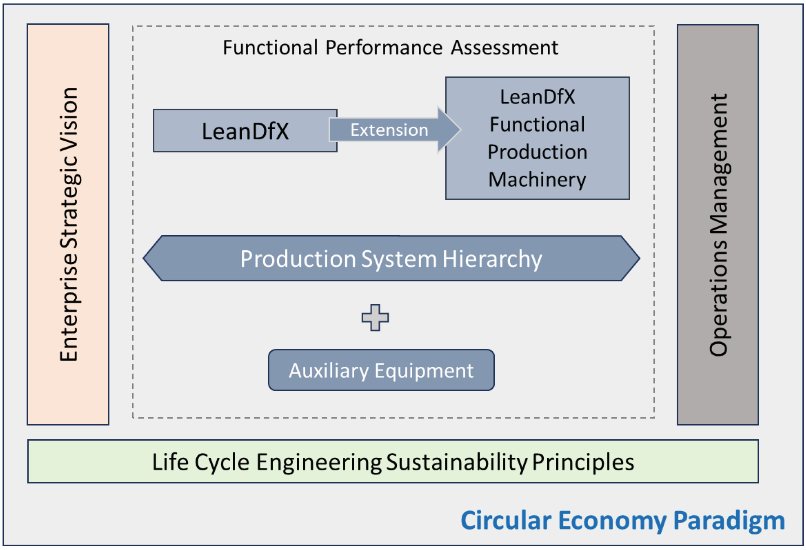

Fig. 1. Conceptual architecture of multidimensional evaluation of production systems design approach.

The architecture foundations share the same life cycle engineering mindset as already used in LeanDfX, but now explicitly adopting the two main pillars: sustainability (triple bottom line of economic, environmental, and social aspects), and circular economy paradigm.

3 Renée Project's Remanufacturing Application

RENÉE project aims to accelerate technological advancement by focusing on human-centric production systems, enhanced with AI, for unblocking remanufacturing circular business models. Another main goal is to enhance Circular Economy principles on production, such as the enhancement of remanufacturing, to intent reduction of waste either from material resources, energy, time, components, or capital good actives. In Table 1 is mapped, described and qualitative evaluated for its relevance, the production systems X dimensions that are expected to be more relevant for future remanufacturing plants. Some of the key dimensions are intrinsically related to sustainability and circularity aspects and others to operations associated to de-manufacturing such as disassembly, flexibility, cost, automation, inspection, etc. and therefore evaluated as high relevance to the production line for remanufacturing or other production cells for other R-strategies (repair, refurbish, retrofit, reuse).

Table 1. Production Systems X dimensions envisioned to remanufacturing plants.

X Dimension	Description in Production Context	Relevance
Design for Cost	Competitive costs, improving profitability, efficiency, and market competitiveness	+++
Design for Logistics	Reduced transport waste, and reverse logistics efficiency. Durable packaging prevents damage in multiple transport cycles	+++
Design for Reliability	Process operation with minimized failure probability	+
Design for Automation	Identify automatable tasks Focus on process standardization	++
Design for Disassembly	Clear instructions for the disassembly workers. Reduced lead times and downtime	+++
Design for Flexibility	Allows adaptations to product variations without significant downtime or retooling, and quick reaction to changing market demands	++
Design for Maintainability	Helps minimize downtime and maintenance costs of equipment and tooling	+
Design for Inspection	Improved quality control, reduced re-work and enhanced worker safety	++
Design for Cleaning	Prevent dirt accumulation in critical areas and improve product quality. Reduced rework	+
Design for Testing	Early identification of issues, minimizing rework and production delays	++
Design for Circularity	Promote R-Strategies, reuse, repair, refurbish complementary to remanufacturing	+++
Design for Economics	Economic viability and creation of a sustainable and circular business model	+++
Design for Social Impact	Promote inclusion and reduce negative social impacts as job displacement for example	++
Design for Environment	Minimization of resource consumption, waste generation, pollution and promoting energy efficiency	+++

4 Conclusions

This work presents a novel decision support approach for production systems design, via a multi-dimensional performance assessment supported on the principles of complex product design DfX. It was based on the original LeanDfX product framework, but coherently integrating with different production knowledge areas and strategic paradigms: as Strategic Enterprise Vision, Lean manufacturing, Operations Management, Sustainability and Circular Economy. The translational strategy of extending and transforming the LeanDfX framework was described along the new architecture presentation. Regarding remanufacturing specific production systems design, key "X dimensions" were defined.

Despite the new approach potential, further work must be carried on to study performance aggregation strategies of LeanDfX multi-machine and equipment assessment, detail each X dimension of a production system design, and achieve process-level LeanDfX integration in production systems relating also the factory and enterprise management aspects. Finally, the inclusion of optimization & digital tools is also envisioned as key assets for extracting the full potential of the framework, as well as, the integration into production systems digital twins and discrete simulation tools. As the product DfX methodologies did in the past, the novel approach can also allow a better communication technical language and explicit trade-off mapping between different X, to ensure all decisions are transmitted effectively between departments and different factory knowledge area, at design stage.

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