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Integrating LeanDfX into PLM Tools to Enhance Efficiency and Effectiveness in Product Development

T. I. Gonçalves[1,*], R. Ramalho[2,] B. Sousa[2] , R.Campilho[2] , P. Vieira[3], R.Cardoso[3], I. Caetano[3], A. Gouveia[4], F. Ribeiro[5] and F. V. Barbosa[6]

[1] INEGI, Campus da FEUP, Rua Dr. Roberto Frias, 400, Porto 4200-465, Portugal
[2] ISEP, Instituto Superior de Engenharia do Porto, Porto, Portugal
[3] SISTRADE, Travessa da Prelada 511 Ramalde 4100-215, Portugal
[4] CEI by ZIPOR, Rua dos Acores 278 São João da Madeira 3700-018, Portugal
[5] JPM Industry, Zona industrial do Rossio Apartado 161 3731-901 Vale de Cambra, Portugal
[6] LAETA, INEGI, Campus da FEUP, Rua Dr. Roberto Frias, 400, Porto 4200-465, Portugal

Abstract

In an era of sharp competition and increasing customer expectations, optimizing the product design and development process is critical to deliver value-added solutions. This study explores the application of a PLM tool with a Lean (Design for Excellence) module integrated to enhance product development efficiency and effectiveness. The LeanDfX module incorporates lean principles with advanced design for X methodologies, enabling the systematic identification and incorporation of value-generating features into products. The proposed methodologies were embedded into a software platform based on versatility, ensuring its flexibility and adaptability to diverse industrial sectors and product categories. These features allow companies across various sectors to benefit from streamlined processes, enhanced collaboration, and reduced development cycle times. A baseline assessment of existing processes was then conducted, serving as a reference point to evaluate performance gaps and opportunities. Building on these insights, corrective and improvement actions were applied, directly informed by the baseline findings. In Case Study 1, the implementation of LeanDfX led to an increase in efficiency, achieving a 34.67% improvement in the displacement and 97.67% enhancement in mass, values that were critical in the baseline analysis. In Case Study 2, the implementation of LeanDfX demonstrated an increase of efficiency through a 98.84% improvement in the Gripping Area of 150 mm², an upgrade in Gripping Area of 550 mm² of 27.32% and a 67.02% enhancement in mass, values that needed to be addressed to ensure the proper functionality of the gripper. By incorporating baseline-driven evaluation and iterative refinement, the approach demonstrated that PLM serves both as a tool for continuous improvement in existing systems and as a strategic framework for guiding innovation during product conception and development.

Keywords: Digitalization, Industry 4.0, Industrial Processes, Lean DfX, PLM

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1. Introduction

Product Lifecycle Management (PLM) tools have reshaped the way industries conducted the design, development, and delivery of products [1], [2]. These platforms establish a centralized and integrative environment for managing streams of information, coordinating processes, and optimizing the use of organizational resources [3]. By acting as digital backbones for product innovation, PLM systems enhance collaborative engineering, enable communication across stakeholders, and ensure traceability throughout the lifecycle [4]. This consolidation

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[*] Corresponding author. Email: tgoncalves@inegi.up.pt

of data supports informed decision-making and accelerates innovation by transforming dispersed knowledge into actionable insights [3], [5]. As industries transition through rapid digitalization, the adaptability of PLM systems to assimilate modern product development paradigms, such as Agile, Lean, and data-driven design, is becoming increasingly critical [6]. In addition, the integration of PLM with Industry 4.0 technologies, such as IoT, cloud computing, and cyber-physical systems, has expanded its role toward enabling digital twins, predictive analytics, and real-time decision-making [7], [8]. Different product development methodologies have significantly influenced the evolution of engineering workflows. Design for Six Sigma, derived from Six Sigma quality principles, embeds statistical tools and structured frameworks, such as Define, Measure, Analyze, Design, Verify, into the early design stages to ensure reliability, consistency, and defect prevention [9]. This proactive approach emphasizes data-driven optimization of product designs before production. Conversely, Agile Product Development, with roots in software engineering, prioritizes iterative cycles, customer-centricity, and cross-functional teamwork [10]. Agile methodologies enabled industries to shorten time-to-market, increase responsiveness to shifting requirements, and cultivate innovation through rapid prototyping and continuous improvement. Complementing these approaches, lean principles, focused on eliminating waste and maximizing value, have become essential drivers of organizational transformation, enhancing efficiency and customer value across sectors [11], [12], [13]. Building upon lean foundations, LeanDfX has emerged as a holistic strategy that integrates Lean philosophy with Design for Excellence (DfX) principles [14], [15], [16]. This methodology enhances critical design dimensions such as manufacturability, sustainability, assembly efficiency, maintainability, and circularity. By embedding Lean thinking within DfX frameworks, organizations can reduce costs and increase performance as well as alignment with broader sustainability goals and extended product longevity [17], [18]. LeanDfX therefore serves as a critical bridge between technical optimization and strategic value creation, reducing overengineering, minimizing waste, and bolstering lifecycle performance [19]. Moreover, LeanDfX directly supports sustainability-oriented practices such as design for disassembly, remanufacturing, and closed-loop material flows, aligning with circular economy principles and policy-driven requirements [20]. Despite their individual contributions, PLM and LeanDfX are often approached as separate streams in research and practice. Yet, their integration creates a powerful synergy that addresses the growing complexity of product development [13], [14]. PLM, when enriched with LeanDfX methodologies, enables organizations to embed lean-driven design criteria directly into lifecycle management platforms. This ensures that iterative design decisions remain both technically robust and economically viable [21]. Such integration strengthens the capacity to identify inefficiencies, anticipate lifecycle bottlenecks, and support modular, scalable design strategies The inclusion of artificial intelligence and machine learning further enhances this integration by enabling design-space exploration, anomaly detection, and lifecycle prediction [22]. Furthermore, as digital technologies advance, this integration can be enhanced through artificial intelligence, digital twins, and predictive analytics. In this context, it can be stated that PLM platforms equipped with LeanDfX streamline design processes and enable simulation-based optimization, scenario testing, and real-time performance monitoring, transforming PLM from a static data repository into an active decision-support system, guiding both operational choices and long-term strategic planning [23]. This integration is particularly relevant for managing sustainability targets, ensuring regulatory compliance, and aligning design outputs with circular economy principles, resulting in a comprehensive framework where strategic lifecycle management and operational design optimization converge.

This study therefore addresses the pressing challenge of balancing operational efficiency with the increasing complexity of product development, by emphasizing the integration of PLM and LeanDfX into a software tool. This tool intends to provide an agile solution by integrating a straightforward approach into the product design and development process, thereby enhancing the creation of value-added products. To demonstrate the relevance of this approach, the PLM and LeanDfX tools will be implemented into two use cases.

2. Methodology

The successful integration of Lean DfX principles within a PLM tool requires a clear definition of functional and operational requirements. These requirements ensure that the tool can deliver tangible value across various product development contexts. A foundation is formed for incorporating lean-oriented decision-making into the design process, facilitating the systematic identification, evaluation, and integration of value-adding features while removing unnecessary elements. From a methodological perspective, these requirements go beyond basic functional compatibility with the PLM platform. They include the structural, procedural, and analytical capabilities necessary to align design activities with lean objectives, such as minimizing waste and optimizing lifecycle costs [24]. Achieving this alignment demands robust data handling and process mapping capabilities and mechanisms for multi-criteria evaluation, real-time feedback, and interdisciplinary collaboration. By clearly defining these requirements from the outset, the Lean DfX module can be configured as a dynamic, context-adaptive decision support system within the PLM framework [25]. This setup ensures that lean principles are applied in a consistent, measurable, and repeatable manner, regardless of the industrial sector or product category in which the tool is used. The following subsections outline the key technical, procedural, and usability requirements that support the integration of Lean DfX into a PLM environment.

2.1. Functional Requirements vs LeanDfX Implementation on the PLM tool

2.1.1 Product Functional Tree

The Product Functional Tree provides a structured breakdown of a product's functions into hierarchical levels, enabling traceability from high-level objectives down to detailed component functionalities. In a PLM environment, this module is crucial for ensuring that design choices align with functional requirements. It allows for the early identification of redundancies, gaps, or features that do not add value. From a LeanDfX perspective, the functional tree serves as a repository of functions and as a way to assess the contribution of each function to customer value, manufacturability, sustainability, and overall lifecycle efficiency. This foundational step is essential for later evaluations of the machine's efficiency and effectiveness. The platform requirements were the foundation for the LeanDfX module integration into the software, considering the following information sectors: construction, visualisation, and edition of the product tree, which involves cataloguing component names and IDs and costs while designating each item as either a "parent" or a "child". The visualisation of this module is available in Fig.1.

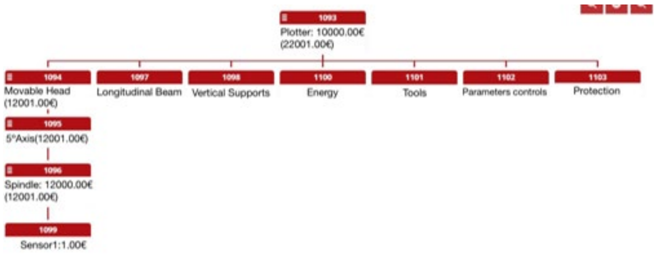


Figure 1. Product Functional Tree module

2.1.2 Maintenance of KPIs

After the construction of the product tree, the software includes a specialized KPI maintenance tab for managing all performance metrics related to the study. The Maintenance of KPIs module ensures that product development activities are continuously measured against strategic objectives and operational efficiency targets. Within a PLM environment, KPIs offer a quantitative basis for progress assessment, facilitating decision-making, and ensuring alignment with Lean principles. From a LeanDfX perspective, monitoring and maintaining KPIs is essential for eliminating waste, identifying performance bottlenecks, and ensuring that design decisions consistently focus on value creation throughout the product lifecycle. Users can then explore a well-organized list of available KPIs and create custom KPIs to address specific project requirements. This flexibility is particularly beneficial when unique project parameters need specialized metrics. By allowing the customization of KPIs, giving them names and IDs, the software ensures that they align with the study's objectives and the specific characteristics of the product . This KPIs are then saved in the system, for future utilizations and future rectifications. These functionalities are illustrated in Fig. 2.

New KPI

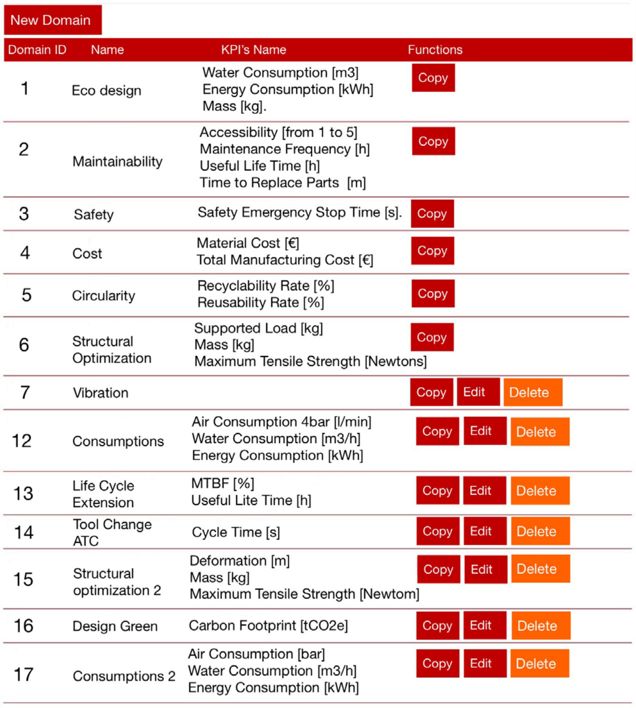
KPI ID	KPI's Name	Functions
1	Energy Consumption [kWh]	
2	Water Consumption [m3]	
3	Mass [kg]	
4	Useful life time [h]	
5	Maintenance Periodicity [h]	
6	Accessibility [from 1 to 5]	
7	Time for Part Exchange [m]	
8	Emergency Stop Time [s]	
9	Total Manufacturing Cost [€]	
10	Material Cost [€]	
11	Recycleability Rate [%]	
12	Reuseability Rate [%]	
13	Supported Load [Kg]	
14	Maximum Tensile Strength [Newtons]	
19	Air Consumption 4bar [l/min]	Edit Delete
21	Cycle Time [s]	Edit Delete
22	Displacement [m]	Edit Delete
23	Carbon Footprint [tCO2e]	Edit Delete
24	Mean Time Between Failures [%]	Edit Delete
25	Water Consumption [m3/h]	Edit Delete
26	Compressed Air [bar]	Edit Delete

Figure 2. Maintenance of KPIs module

2.1.3 Maintenance of Domains

The Maintenance of Domains module facilitates the organized management of product-related knowledge within the PLM environment. Domains act as containers for grouping information, requirements, and design elements based on technical disciplines, lifecycle stages, or value streams. This structure ensures consistency and traceability throughout the development process. From a LeanDfX perspective, maintaining domains is essential for reducing redundancy, enhancing cross-functional collaboration, and aligning product data with customer value and lifecycle efficiency. Once users define their KPIs, they can customize the maintenance domains with a unique name within the software platform. The system comes preloaded with standard domains, but it also allows for modifications or the creation of tailored domains to meet specific operational needs. This customization ensures that the evaluation framework is aligned with the characteristics of each product.

The user-friendly interface facilitates efficient updates or the development of new domains, enabling users to specify their KPIs and acceptable parameters for a personalized evaluation strategy. The customizable maintenance domains, illustrated in Fig. 3, demonstrate the platform's structure and the connection between domains and KPIs. The platform's robust functionality enhances adaptability, supports precise evaluations, and enables thorough performance analysis, ultimately driving continuous improvement in product design and maintenance methods. These domains are then saved in the system, for future utilizations and future rectifications . All the requirements of this module were complied.

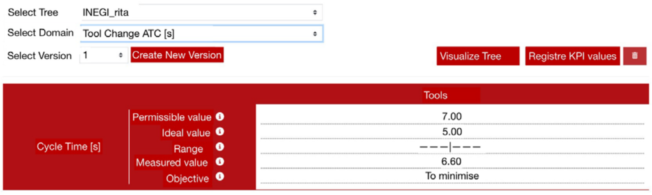


Domain ID	Name	KPI's Name	Functions
1	Eco design	Water Consumption [m3] Energy Consumption [kWh] Mass [kg].	Copy
2	Maintainability	Accessibility [from 1 to 5] Maintenance Frequency [h] Useful Life Time [h] Time to Replace Parts [m]	Copy
3	Safety	Safety Emergency Stop Time [s].	Copy
4	Cost	Material Cost [€] Total Manufacturing Cost [€]	Copy
5	Circularity	Recyclability Rate [%] Reusability Rate [%]	Copy
6	Structural Optimization	Supported Load [kg] Mass [kg] Maximum Tensile Strength [Newtons]	Copy
7	Vibration		Copy Edit Delete
12	Consumptions	Air Consumption 4bar [l/min] Water Consumption [m3/h] Energy Consumption [kWh]	Copy Edit Delete
13	Life Cycle Extension	MTBF [%] Useful Lite Time [h]	Copy Edit Delete
14	Tool Change ATC	Cycle Time [s]	Copy Edit Delete
15	Structural optimization 2	Deformation [m] Mass [kg] Maximum Tensile Strength [Newtom]	Copy Edit Delete
16	Design Green	Carbon Footprint [tCO2e]	Copy Edit Delete
17	Consumptions 2	Air Consumption [bar] Water Consumption [m3/h] Energy Consumption [kWh]	Copy Edit Delete

Figure 3. Maintenance of Domains module

2.1.4 KPI Matrix Module

The KPI Matrix module offers a structured framework for connecting performance indicators with specific product development objectives, processes, and design choices within the PLM environment. From a LeanDfX perspective, this matrix is essential for ensuring that measurements are not isolated but are instead aligned with customer value, manufacturability, sustainability, and lifecycle efficiency. This module involves establishing connections between the KPIs and their respective domains within the KPI Matrix, connecting each KPI to the nodule of the product tree. These KPIs, that can be edited at any time, are displayed in a form of a Matrix. These objectives generally fall into one of three categories: Minimize, Maximize, or Maintain within a defined Tolerance Range, as illustrated in Fig. 4. These objectives define the barriers of the 'Ideal Value', 'Acceptance Range' and 'Measured Value' that will be the values used to calculate the Efficiency and Effectiveness of each KPI. Additionally, it is crucial to set acceptable thresholds for each KPI, which can be a single allowable value, an optimal target, or a specified range that indicates the desired performance level. After defining these parameters, the user must input the actual measured values for each KPI. These values are vital to the analytical framework, as they will help calculate the efficiency and effectiveness of each component. This approach contributes to a comprehensive performance assessment, enabling data-driven decision-making in the subsequent phases.



Select Tree: INEGI_rita
Select Domain: Tool Change ATC [s]
Select Version: 1

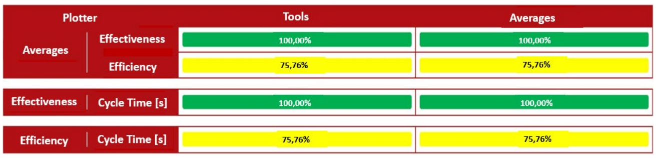
Cycle Time [s]
Permissible value: 7.00
Ideal value: 5.00
Range: – – –|– – –
Measured value: 6.60
Objective: To minimise

Figure 4. KPI Matrix Module

2.1.5 Scorecards

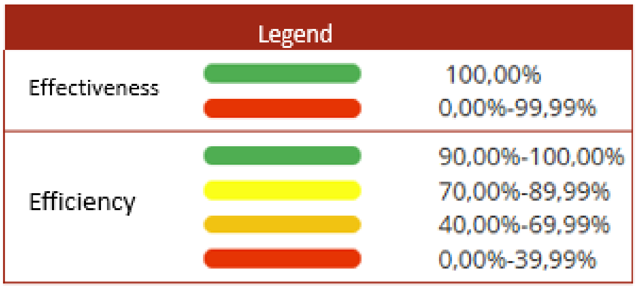
The Scorecards module allows for the aggregation and visualization of performance data, offering a clear overview of how product development activities align with strategic goals and operational targets. Within PLM environment, scorecards serve as decision-support tools by consolidating KPIs, functional requirements, and project milestones into an accessible format for stakeholders. From a LeanDfX perspective, scorecards are crucial for monitoring value delivery, identifying inefficiencies, and ensuring that design decisions are driven by data-based insights throughout the product lifecycle.

The final step of the process involves a detailed analysis of the scorecards generated by the software across the chosen domains, focusing on two key dimensions: effectiveness and efficiency that is possible to select within the product tree . Within the LeanDfX framework, effectiveness is defined as the ability of a product, process, or system to consistently achieve its specified objectives and requirements while meeting the expectations of all stakeholders. This understanding of effectiveness allows outcomes to be categorized as either entirely successful or completely unsuccessful, as shown in Figure 5. In contrast, efficiency refers to the execution of design and development activities using resources optimally, minimizing time, cost, and effort, without compromising quality and desired outcomes. The efficiency of a product can vary significantly, indicating different levels of resource use concerning its effectiveness, further illustrated in Figure 5. Both effectiveness and efficiency are calculated within the numerical formulas required for the correct results and the results are showed in the PLM. This analytical approach clarifies the overall performance of design processes and helps to identify potential areas for improvement and optimisation. The interpretation of the results is on the legend (showed in Figure 6). By carefully examining these metrics, organizations can detect inefficiencies and gaps in effectiveness, enabling targeted enhancements that support both operational performance and stakeholder satisfaction.



Plotter		Tools	Averages
Averages	Effectiveness	100,00%	100,00%
	Efficiency	75,76%	75,76%
Effectiveness	Cycle Time [s]	100,00%	100,00%
Efficiency	Cycle Time [s]	75,76%	75,76%

Figure 5. Scorecards Module



Legend		
Effectiveness	🟩	100,00%
	🟥	0,00%-99,99%
Efficiency	🟩	90,00%-100,00%
	🟨	70,00%-89,99%
	🟧	40,00%-69,99%
	🟥	0,00%-39,99%

Figure 6. Results Legend in the Scorecards Module

2.2. Case Studies and Use-Cases

This study presents two case studies that illustrate the application of the PLM tool within the LeanDfX implementation. The case studies are referred to as Case Study 1 and Case Study 2, both focusing on the Design for Maintainability.

Case Study 1 demonstrates the application of LeanDfX methodology in optimizing a stone-cutting machine designed and constructed by a leading Portuguese company specialized in advanced manufacturing technologies. The focus is on the optimization of an ornamental stone-cutting machine model, illustrated in Figure 7, to improve its capabilities and strategically position the company for sustained competitiveness in the market. The main functional requirements defined for this case included: (i) maintaining structural stiffness under cutting loads, (ii) ensuring maximum displacement below 0.20 mm, (iii) facilitating easier access for maintenance operations, and (iv) reducing the total mass and material consumption without affecting machine stability. Addressing these objectives is essential for increasing machine performance and maintainability, optimising resource usage, and sustaining profitability without compromising environmental integrity.

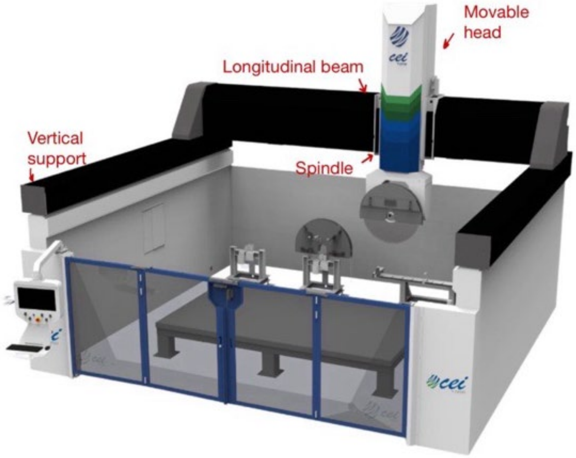


Figure 7. Machine of Case Study 1

In Case Study 2, the effectiveness of the LeanDfX tool is for the design of a new robotic gripper for integration into the product portfolio of a Portuguese company in the intralogistics sector, focusing on robotic systems and automation solutions. This initiative aims to create a robotic gripper for collaborative robots used for cardboard box palletization, as it can be seen in Figure 8. The requirements established for this product development included: (i) adaptability to different box dimensions, (ii) payload capacity of up to 15 kg, (iii) low overall weight to minimise inertia during robot motion, (iv) modularity for easy component replacement, and (v) compliance with ISO 10218 safety standards for collaborative operations. The LeanDfX methodology was crucial for the selection of the most efficient concept and design ensuring optimal functionality and sustainability.

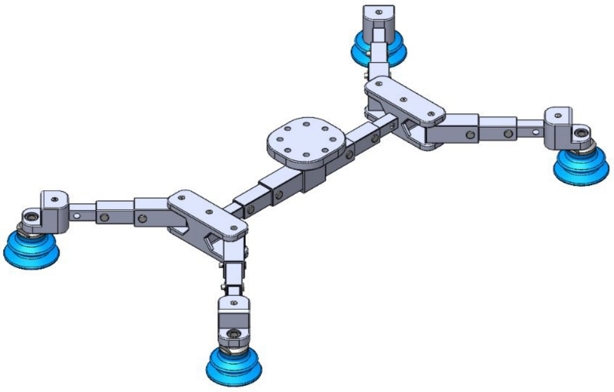


Figure 8. Initial Concept of Case Study 2

The primary distinction between the two case studies concerns the phase of the product design and development process. In Case Study 1, LeanDfX is implemented on the prototyping phase, allowing to optimize the existing design through targeted modifications. In contrast, Case Study 2 applies LeanDfX at the early stage of the development phase, specifically in the conceptualization and product detail prior prototyping Together, these case studies demonstrate the versatility of the LeanDfX module integrated into the PLM software.

3. Results and Discussion

This section comprises two sub-sections. The first sub-section presents baseline results from two case studies, using LeanDfX to determine initial values for selected KPIs and establish a reference for comparison. The second sub-section details the implementation of design modifications in both case studies and subsequent assessments to evaluate the impact of these changes. This structure enables direct comparison between baseline and revised designs, demonstrating the effectiveness of the modifications and their influence on the KPIs.

3.1. Baseline

The primary objective of this research is to assess a concept for potential integration into the company's existing product portfolio, focusing on its feasibility, market relevance, and innovation. The application of the LeanDfX module using the PLM platform will focus on specific domains, considered by the use cases as relevant to increase their market competitiveness.

3.1.1. Case Study 1

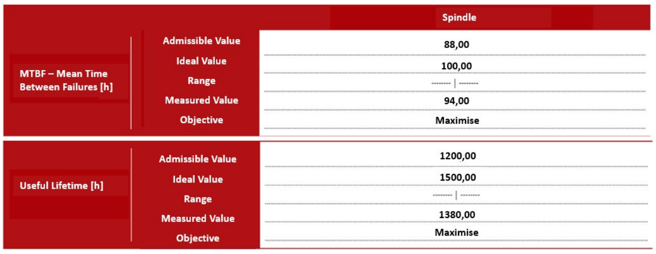
In Case Study 1, the company focuses on four critical indicators related to the maintainability domain:

- Life Cycle Extension
- Structural Optimisation
- Design Green
- Tool Change

For Life Cycle Extension, the main KPIs selected were Mean Time Between Failures (MTBF) and the useful lifetime of the spindle, which is a crucial and vulnerable component susceptible to operational wear. The significant costs associated with spindle replacement underscore its importance in the overall maintenance strategy.

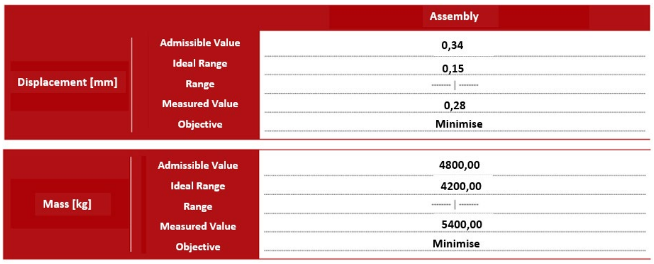
In Structural Optimisation, two relevant KPIs were identified: mass of the assembly and displacement of the assembly (the assembly is composed by two key components of the machine - vertical supports and longitudinal beam). These parameters are essential for evaluating both the structural integrity and operational performance of the machine. In the Design Green domain, the KPI of carbon footprint was considered responsible for the Sustainability part of this evaluation. Regarding Tool Change, Cycle Time was identified as the KPI that quantifies the efficiency of tool transitions on the machine.

The use case provided clear performance criteria for each KPI, defining acceptable, ideal, and actual values, along with specific objectives. A detailed representation of these findings is illustrated in Figures 9, 10, 11 e 12 which further depict the performance metrics.



		Spindle
MTBF – Mean Time Between Failures [h]	Admissible Value	88,00
	Ideal Value	100,00
	Range	-------- | --------
	Measured Value	94,00
	Objective	Maximise
Useful Lifetime [h]	Admissible Value	1200,00
	Ideal Value	1500,00
	Range	-------- | --------
	Measured Value	1380,00
	Objective	Maximise

Figure 9. Life Cycle Extension Domain matrix of Baseline of Case Study 1



		Assembly
Displacement [mm]	Admissible Value	0,34
	Ideal Range	0,15
	Range	-------- | --------
	Measured Value	0,28
	Objective	Minimise
Mass [kg]	Admissible Value	4800,00
	Ideal Range	4200,00
	Range	-------- | --------
	Measured Value	5400,00
	Objective	Minimise

Figure 10. Structural Optimisation Domain matrix of Baseline of Case Study 1

		Assembly
Carbon footprint [tCO_2e]	Admissible Value	69,00
	Ideal Range	54,00
	Range	-------- | --------
	Measured Value	80,80
	Objective	Minimise

Figure 11. Design Green Domain matrix of Baseline of Case Study 1

		Tools
Cycle Time [s]	Admissible Value	7,00
	Ideal Range	5,00
	Range	------- | -------
	Measured Value	6,60
	Objective	Minimise

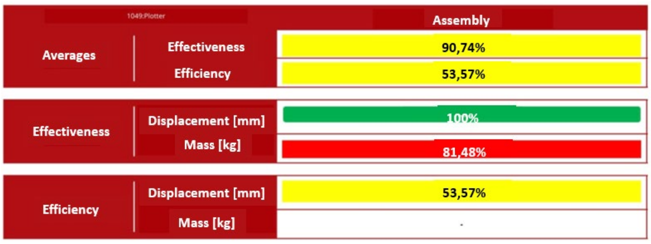
Figure 12. Tool Change Domain matrix of Baseline of Case Study 1

In the context of Life Cycle Extension, as shown in Figure 13, both effectiveness and efficiency metrics demonstrate to be aligned with the company's requirements. As a result, this domain is classified as stable and high-performing, leading the company to focus its future improvement efforts on other areas rather than making changes in this sector.

1095 : 5°Eixo		Spindle	Médias
Mean	Effectiveness	100,00 %	100,00 %
	Efficiency	93,00 %	93,00 %
Effectiveness	MTBF - Mean Time Between Failures [h]	100,00 %	100,00 %
	Useful Lifetime [h]	100,00 %	100,00 %
Efficiency	MTBF - Mean Time Between Failures [%]	94,00 %	94,00 %
	Useful Lifetime [h]	92,00 %	92,00 %

Figure 13. Scorecards of the Life Cycle Extension domain of Baseline of Case Study 1

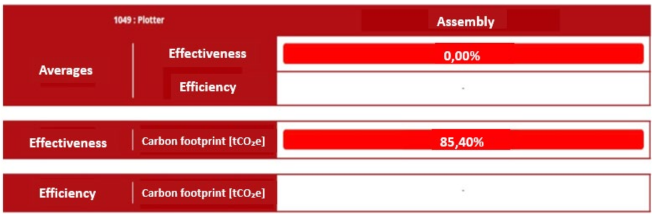
In the domain of Structural Optimization, as shown in Figure 14, the evaluation of the displacement and mass reveals an efficiency rating in mass in 0 % and 53.57 % in displacement. This shows an urgent need to reassess these KPIs and brainstorm for new solutions that comply better with the requirements made by the company.



1049:Plotter		Assembly
Averages	Effectiveness	90,74%
	Efficiency	53,57%
Effectiveness	Displacement [mm]	100%
	Mass [kg]	81,48%
Efficiency	Displacement [mm]	53,57%
	Mass [kg]	-

Figure 14. Scorecards of the Structural Optimisation domain of Baseline of Case Study 1.

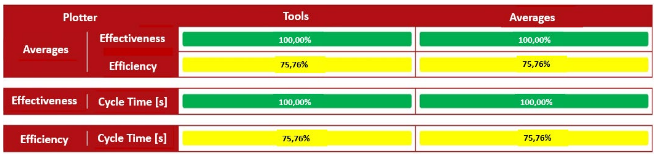
In the domain of Design Green, as shown in Figure 15, the evaluation of the Carbon Footprint KPI reveals a non-existent rating for efficiency. This result is due to recorded values exceeding permissible tolerance thresholds, indicating a significant deviation from the specified performance criteria. This failure to meet the established specifications highlights an urgent need for a thorough reassessment and possible recalibration to ensure compliance with the company's requirements.



1049 : Plotter		Assembly
Averages	Effectiveness	0,00%
	Efficiency	-
Effectiveness	Carbon footprint [tCO₂e]	85,40%
Efficiency	Carbon footprint [tCO₂e]	-

Figure 15. Scorecards of the Design Green domain of Baseline of Case Study 1

In the Tool Change domain, as illustrated in Figure 16, the analysis shows that the KPI effectiveness is currently at 100 %. This indicates that tool changes are being executed seamlessly and are in line with the specified objectives and outcomes. Conversely, the efficiency metric stands at 75.8%. While this figure is slightly below the optimal benchmark, it remains within a reasonable range, suggesting potential for improvement without highlighting any critical issue. Overall, based on the performance metrics, the current state in this area poses no significant concerns for the use case, as both the effectiveness and efficiency metrics are within acceptable parameters.



Plotter		Tools	Averages
Averages	Effectiveness	100,00%	100,00%
	Efficiency	75,76%	75,76%
Effectiveness	Cycle Time [s]	100,00%	100,00%
Efficiency	Cycle Time [s]	75,76%	75,76%

Figure 16. Scorecards of the Tool Change domain of Baseline of Case Study 1

3.1.2. Case Study 2

In Case Study 2, which focuses on Product Design Efficiency, KPIs were identified to assess system efficiency and reliability. The selected KPIs included Gripping Areas, Modularity and Weight of the Gripper Structure.

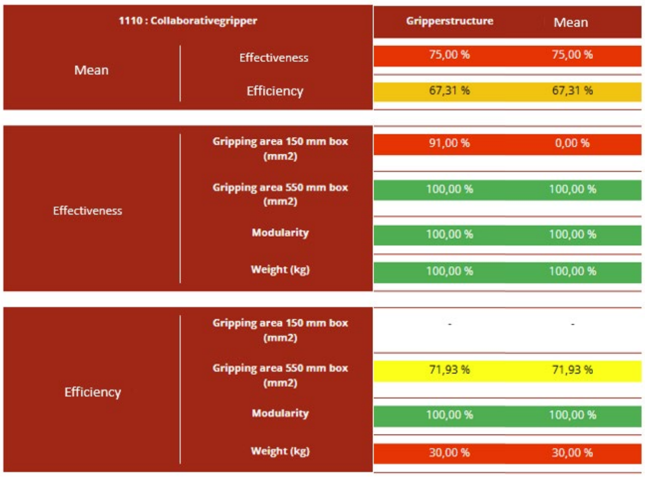
For each KPI, the company defined specific parameters, including acceptable values, ideal benchmarks, and actual measured outcomes. These details are visually represented in Figure 17, providing a comprehensive view of the performance expectations and metrics related to maintainability.

		Gripperstructure
Gripping area 150 mm box (mm2)	Admissible Value	8000,00
	Ideal Value	8500,00
	Range	-------- | --------
	Measured Value	7280,00
	Objective	Maximizar
Gripping area 550 mm box (mm2)	Admissible Value	120000,00
	Ideal Value	175000,00
	Range	-------- | --------
	Measured Value	125882,00
	Objective	Maximizar
Modularity	Admissible Value	10,00
	Ideal Value	25,00
	Range	-------- | --------
	Measured Value	25,00
	Objective	Maximizar
Weight (kg)	Admissible Value	1,50
	Ideal Value	1,30
	Range	-------- | --------
	Measured Value	0,39
	Objective	Minimizar

Figure 17. Product Design Efficiency domain matrix of Baseline of Case Study 2

Based on the results, shown in Figure 18, an analysis was then conducted to assess the efficiency and effectiveness for the gripper structure. This analytical approach provided valuable insights into the operational efficiency of these components, particularly focusing on the pneumatic materials used in the gripper assembly. Notably, the gripping area of 150 mm² was identified as the least efficient segment during the assessment, not achieving an efficient score, meaning that the measured values were out of the ideal ones. This inefficiency highlights the urgent need for improving this requirement. Further assessment of the performance metrics revealed that the efficiency levels of weight recorded an efficiency of 30 %. These findings not only indicate a critical area requiring immediate intervention but also present a potential risk to overall operational efficiency.

Moreover, the broader evaluation suggests a misalignment between the product's efficiency and the established objectives for each KPI. This discrepancy underscores the need for a strategic reassessment of the product's design and operational processes. Such a reassessment is essential to ensure that performance outcomes are aligned with the company's requirements, improving the efficiency and effectiveness of the product design.



1110 : Collaborativegripper		Gripperstructure	Mean
Mean	Effectiveness	75,00 %	75,00 %
	Efficiency	67,31 %	67,31 %
Effectiveness	Gripping area 150 mm box (mm2)	91,00 %	0,00 %
	Gripping area 550 mm box (mm2)	100,00 %	100,00 %
	Modularity	100,00 %	100,00 %
	Weight (kg)	100,00 %	100,00 %
Efficiency	Gripping area 150 mm box (mm2)	-	-
	Gripping area 550 mm box (mm2)	71,93 %	71,93 %
	Modularity	100,00 %	100,00 %
	Weight (kg)	30,00 %	30,00 %

Figure 18. Scorecards of the Product Design Efficiency domain of Baseline of Case Study 2

3.2. Final Assessment

This sub-section presents the results obtained after implementing corrective actions based on the baseline assessment using the LeanDfX module, with a focus on the inefficiencies detected. Improvements on the prototype, in case study 1, and design detail in use case 2, were conducted and a final validation using LeanDfX was performed using PLM. The objective of this approach is dual: first, to validate whether targeted modifications informed by LeanDfX principles can effectively enhance the alignment between functional requirements and PLM tool performance; and second, to demonstrate the iterative nature of the methodology, where evaluation and refinement operate as a continuous cycle. By concentrating on the areas with the lowest initial performance, this process not only improves specific functional outcomes but also reveals the broader impact of LeanDfX-driven optimization across the PLM system.

3.2.1 Case Study 1

Analyzing the baseline, mass and displacement had lower values of efficiency. Therefore, these KPIs were the first to be addressed . Following this assessment, it is also essential to evaluate the critical components such as the longitudinal beam and the vertical supports of the machine and provide solutions to improve these results and consequently the machine.

Different internal geometries aimed at improving stiffness while reducing material usage, were selected and a structural analysis was conducted to comply with functionality and sustainability . For the longitudinal beam, several internal geometrical modifications were tested, with particular emphasis on cross internal structures that could reduce material usage while maintaining stiffness. Among these, the I-shaped design in the longitudinal beam with the addiction of the extra leg (showed in Figure 19), emerged as the most balanced and technically feasible solution. Although certain lightweight materials offered more substantial mass reductions, around 4300 kg. Although this solution is not the lowest-cost alternative in absolute terms, it demonstrated high potential for implementation due to its consistent structural behavior and lower environmental impact per kilogram of material used.

The addition of a central reinforcement leg combined with an I-shaped internal geometry for the longitudinal beam represents the most technically robust and sustainable configuration for the vertical supports. This design enhances the distribution of mechanical stresses. The study followed a static structural setup, in which the vertical supports were fixed at their base while subjected to gravitational forces and an additional vertical load of 2000 kg applied to the longitudinal beam, replicating the operational load of the machine's movable head. The mesh was generated using a blended curvature-based meshing method with local refinements applied to regions of stress concentration. The final mesh was validated through a convergence study, ensuring result stability with variations below 2%. The maximum observed displacement was 0.17 mm, demonstrating compliance with technical requirements and improved sustainability through optimized material use and increased structural efficiency. Additionally, this configuration is cost-effective because it does not require premium materials or advanced manufacturing processes, being this decrease around 13%. The proposed structure is present in Figure 19.

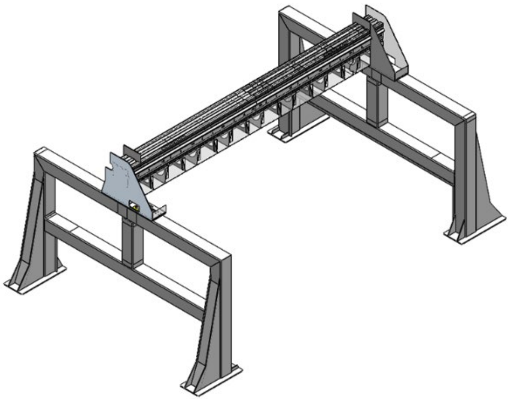
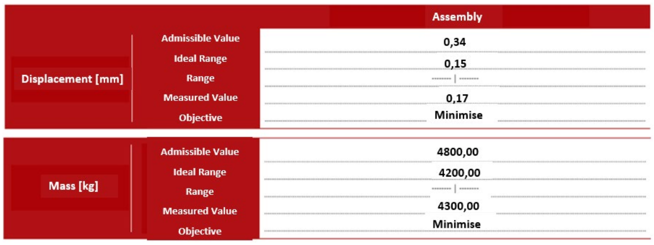


Figure 19. Structure of Case Study 1 with alterations in longitudinal beam and vertical supports

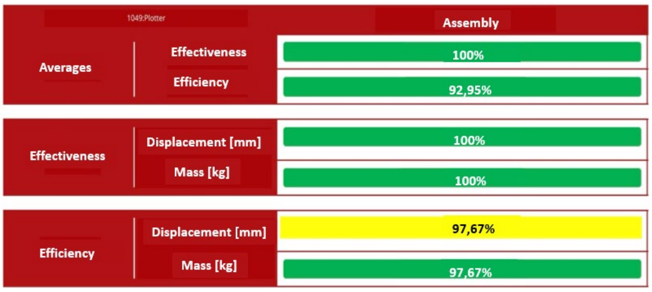
Specifically, key components achieved reductions in mass, displacement, and material costs, supporting both performance and sustainability objectives. Therefore, the implementation of these changes in the simulation generated new results on the efficiency of the assembly, as it can be seen in Figure 20.



		Assembly
Displacement [mm]	Admissible Value	0,34
	Ideal Range	0,15
	Range	-------- | --------
	Measured Value	0,17
	Objective	Minimise
Mass [kg]	Admissible Value	4800,00
	Ideal Range	4200,00
	Range	-------- | --------
	Measured Value	4300,00
	Objective	Minimise

Figure 20. Scorecards of the Structural Optimisation domain of Case Study 1

At the assembly level, efficiency regarding mass and displacement were improved 97.67% and 88.24% compared to the baseline, respectively as it can be seen in Figure 21. These parameters still have to be test within the simulation models, among other changes in the machine required by the company.



1049:Plotter		Assembly
Averages	Effectiveness	100%
	Efficiency	92,95%
Effectiveness	Displacement [mm]	100%
	Mass [kg]	100%
Efficiency	Displacement [mm]	97,67%
	Mass [kg]	97,67%

Figure 21. Scorecards of the Structural Optimisation domain of Case Study 1

New implementations of LeanDfX in Case Study 1 demonstrated an improvement on machine performance. Specifically, efficiency gains were evident through a 34.67% improvement in the Displacement KPI and a 97.67% enhancement in the Mass KPI.

3.2.2. Case Study 2

Analysing the baseline, the gripping area of 150 mm² and the weight had the lowest values of efficiency. Following this evaluation, it is essential to revise the initial concept. The gripping area of 150 mm² was insufficient to securely grasp boxes with that area, thereby failing to satisfy the specified operational requirements.

To guarantee the compliance of the gripping area of 150 mm², the gripper structure was redesigned. Before initiating the optimisation of the gripper components, it was necessary to determine the routing path of the tubing within the gripper structure. After evaluating several hypotheses, it was decided that the tubing would originate from the valves and enter the gripper structure through the gripper mount. This configuration ensured secure routing of the tubing within the gripper structure, minimised the risk of interference during operation, and also allowed gripper adjustment without tubing removal or entrapment, as can be seen in Figure 22. Additionally, as the gripper mount is the component positioned closest to the cobot, this arrangement enabled the tubing to be fastened along the cobot structure rather than being left hanging, which could result in injuries for workers and also potential entanglement during operation.

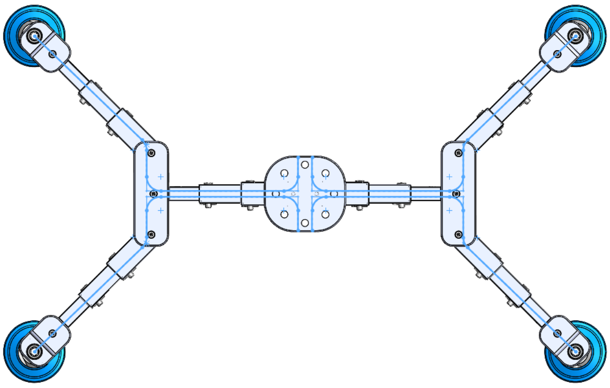


Figure 22. Tubing path inside the gripper structure

Also, it was decided that the telescopic structure original rectangular shape should become rounded, as it can be seen in Figure 23, enabling the telescopic arms to provide an improved gripping area for safer and more ergonomic handling. The tubing length was also increased to ensure that the final model, obtained after the product architecture phase, to achieve a higher level of efficiency according to the LeanDfX scorecard. In addition to optimising the gripping area of 150 mm², the subsequent optimisation of the 550 mm² gripping area built upon the initial improvement, resulting in enhanced efficiency values.

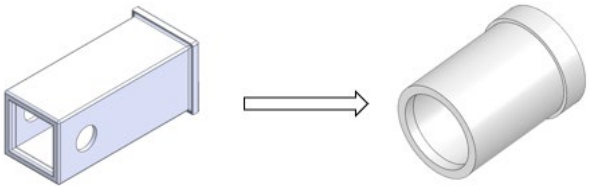


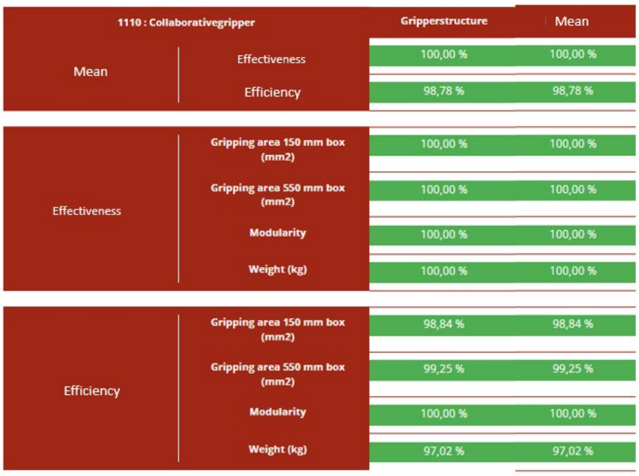
Figure 23. Optimisation of the tubing design.

To assess the weight, SolidWorks® was used to analyse the mass properties of the custom-designed components added to the gripper, while also referencing the datasheet for standardized components. The total estimated mass for the gripper system was around 1.343 kg, which meets the company's requirement of remaining under 1,5 kg. Therefore, the implementation of these changes in the gripper design generated new results on the efficiency of the assembly, as can be seen in Figure 24.

		Gripperstructure
Gripping area 150 mm box (mm2)	Admissible Value	8000,00
	Ideal Value	8500,00
	Range	-------- | --------
	Measured Value	8600,00
	Objective	Maximizar
Gripping area 550 mm box (mm2)	Admissible Value	120000,00
	Ideal Value	175000,00
	Range	-------- | --------
	Measured Value	176323,00
	Objective	Maximizar
Modularity	Admissible Value	10,00
	Ideal Value	13,00
	Range	-------- | --------
	Measured Value	13,00
	Objective	Maximizar
Weight (kg)	Admissible Value	1,50
	Ideal Value	1,30
	Range	-------- | --------
	Measured Value	1,34
	Objective	Minimizar

Figure 24. Scorecards of the Product Design Efficiency domain of Case Study 2

For the Gripper Structure, the KPI of Gripping Area of 150 mm² has now a value of efficiency of 98.84%, the KPI of gripping area of 550 mm² has now a value of 99.25% and the KPI of weight has now a value of 97.02% of efficiency, as it can be seen in Figure 25. These parameters were tested in an experimental validation of the gripper, guaranteeing that the prototype is functional and it complies with his functional requirements. Nonetheless, LeanDfX helped developing several solutions for the gripper, accompanying the increasing or decreasing of the KPIs within each solution.



1110 : Collaborativegripper		Gripperstructure	Mean
Mean	Effectiveness	100,00 %	100,00 %
	Efficiency	98,78 %	98,78 %
Effectiveness	Gripping area 150 mm box (mm2)	100,00 %	100,00 %
	Gripping area 550 mm box (mm2)	100,00 %	100,00 %
	Modularity	100,00 %	100,00 %
	Weight (kg)	100,00 %	100,00 %
Efficiency	Gripping area 150 mm box (mm2)	98,84 %	98,84 %
	Gripping area 550 mm box (mm2)	99,25 %	99,25 %
	Modularity	100,00 %	100,00 %
	Weight (kg)	97,02 %	97,02 %

Figure 25. Scorecards of the Product Design Efficiency domain of Case Study 2

New implementations of LeanDfX in Case Study 2 demonstrated a significant positive impact on system performance. Specifically, efficiency gains were evident through a 98.84% improvement in the Gripping Area of 150 mm², an upgrade in Gripping Area of 550 mm² of 27.32% and a 67.02% enhancement in the Mass KPI. With these design improvements validated by the LeanDfX module, and the product can follow to the product prototyping phase.

4. Conclusions and Future Work

This research emphasises the integration of LeanDfX methodologies into PLM frameworks to enhance product development. It demonstrates improved performance in product design and optimised lifecycle management by aligning PLM tools with LeanDfX principles, thus creating an agile design framework that meets today's industrial needs. The findings indicate that this approach serves as a critical visual tool within the decision-making process, allowing for a comprehensive evaluation of design performance and its alignment with user expectations. It clarifies whether a project is ready to progress or reveals crucial insights into areas that need refinement. By identifying potential modifications early in the development process, it significantly reduces the risk of cost overruns and schedule delays, ensuring a smoother path toward successful project execution. By using PLM software with LeanDfX module, it is possible to visualize the improvement in the machines, to compare different solutions and assess their impact. In Case Study 1, the application of LeanDfX resulted in significant efficiency gains, evidenced by a 34.67% improvement in the displacement and a 97.67% enhancement in the mass , metrics considered critical during the baseline analysis. In this case, LeanDfX was applied to a machine prototype with predefined project boundaries, where the methodology served to adapt and refine the existing design through targeted modifications. This application highlights the value of lean principles in optimising performance and sustainability within a fixed framework. Meanwhile, Case Study 2 showcased the efficiency of LeanDfX with a 98.84% increase in the gripping area at 150 mm², a 27.32% improvement at 550 mm², and 67.02% enhancement in the mass . Unlike Case Study 1, this implementation occurred during the early development phase, specifically in the evaluation and approval of a prototype gripper. In this scenario, LeanDfX informed design decisions, guided the selection of alternatives, and shaped the trajectory of product development. This implementation at the early stage of the design process underscores the LeanDfX ability to influence both technical feasibility and long-term lifecycle outcomes from the outset. Together, the two case studies illustrate the diverse functions of PLM in modern engineering, showing its versatility both in refining established designs and in steering innovation at early design stages. Future research should focus on customising LeanDfX for various industries and products to enhance its applicability. There is significant potential to incorporate emerging technologies like artificial intelligence and digital twins to improve LeanDfX within PLM systems through predictive analytics and real-time optimisation. Additionally, further investigations should rigorously assess the impact of LeanDfX and PLM integration on metrics such as time-to-market, production costs, product quality, and resource utilisation. Research should also explore how LeanDfX can support sustainability efforts through eco-design and circular economy initiatives, thereby deepening the understanding of its transformative potential in product lifecycle management.

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References

[1] T. Fuerst and A. Mazumdar, "Engineering Graphics Education for the Digital Enterprise: A Practical Example in a Large Freshman Engineering Course."

[2] G. Jumaeva, "Using Digital Technology in the Construction Industry," *The Multidisciplinary Journal of Science and Technology*, vol. 4, no. 12, 2024.

[3] P. Barrios, C. Danjou, and B. Eynard, "Literature review and methodological framework for integration of IoT and PLM in manufacturing industry," *Comput Ind*, vol. 140, Sep. 2022, doi: 10.1016/j.compind.2022.103688.

[4] X. Ji and S. Abdoli, "Challenges and Opportunities in Product Life Cycle Management in the Context of Industry 4.0," in *Procedia CIRP*, Elsevier B.V., 2023, pp. 29–34. doi: 10.1016/j.procir.2023.04.002.

[5] D. A. McKendry, R. I. Whitfield, and A. H. B. Duffy, "Product Lifecycle Management implementation for high value Engineering to Order programmes: An informational perspective," *J Ind Inf Integr*, vol. 26, Mar. 2022, doi: 10.1016/j.jii.2021.100264.

[6] K. Dyadyura, G. Oborskyi, I. Prokopovych, V. Khamitov, and M. Holubiev, "Optimal Management in the Operation of Complex Technical Systems," *Journal of Engineering Sciences (Ukraine)*, vol. 11, no. 1, pp. B1–B9, 2024, doi: 10.21272/jes.2024.11(1).b1.

[7] Jasleen Singh Saini, "Integrating PLM and Digital Twin Technologies: A Comprehensive Analysis of Modern Product Development," *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, vol. 11, no. 1, pp. 2626–2636, Feb. 2025, doi: 10.32628/cseit251112264.

[8] B. Govindarajan *et al.*, "Integrating Digital Twin Technology with PLM for Enhanced Product Lifecycle Management," 2024. [Online]. Available: https://www.researchgate.net/publication/387298099

[9] K. Jenab, C. Wu, and S. Moslehpour, "Design for six sigma: A review," 2018, *Growing Science*. doi: 10.5267/j.msl.2017.11.001.

[10] J. Heimicke, S. Kaiser, and A. Albers, "Agile product development: An analysis of acceptance and added value in practice," in *Procedia CIRP*, Elsevier B.V., 2021, pp. 768–773. doi: 10.1016/j.procir.2021.05.046.

[11] E. Rauch, P. Dallasega, and D. T. Matt, "Axiomatic Design Based Guidelines for the Design of a Lean Product Development Process," in *Procedia CIRP*, Elsevier, 2015, pp. 112–118. doi: 10.1016/j.procir.2015.07.005.

[12] A. Taher and M. Al Bashar, "The Impact of Lean Manufacturing Concepts on Industrial Processes' Efficiency and Waste Reduction," *International Journal of Progressive Research in Engineering Management and Science*, vol. 04, no. 06, pp. 338–349, Jun. 2024, [Online]. Available: https://www.researchgate.net/publication/381250819

[13] S. Panigrahi, K. K. Al Ghafri, W. R. Al Alyani, M. W. Ali Khan, T. Al Madhagy, and A. Khan, "Lean manufacturing practices for operational and business performance: A PLS-SEM modeling analysis," *International Journal of Engineering Business Management*, vol. 15, Jan. 2023, doi: 10.1177/18479790221147864.

[14] Y.-C. Wang, S. H. Chan, and Z.-H. Wang, "Lecture Notes in Mechanical Engineering Flexible Automation and Intelligent Manufacturing: Manufacturing Innovation and Preparedness for the Changing World Order." [Online]. Available: https://link.springer.com/bookseries/11693.

[15] M. Abramovici, R. Stark, B. Kreis, and & Wgmk, "Lecture Notes in Production Engineering German Academic Society for Product Development WiGep." [Online]. Available: http://www.springer.com/series/10642

[16] U. Aliende Urrutia, P. Webb, and M. Summers, "Analysis of Design for X Methodologies for Complex Assembly Processes: A Literature Review," in *Volume 4: 19th Design for Manufacturing and the Life Cycle Conference; 8th International Conference on Micro- and Nanosystems*, American Society of Mechanical Engineers, Aug. 2014. doi: 10.1115/DETC2014-34955.

[17] L. Atilano, A. Martinho, M. A. Silva, and A. J. Baptista, "Lean Design-for-X: Case study of a new design framework applied to an adaptive robot gripper development process," in *Procedia CIRP*, Elsevier B.V., 2019, pp. 667–672. doi: 10.1016/j.procir.2019.04.190.

[18] M. Ferrazzi, S. Frecassetti, A. Bilancia, and A. Portioli-Staudacher, "Investigating the influence of lean manufacturing approach on environmental performance: A systematic literature review," *International Journal of Advanced Manufacturing Technology*, vol. 136, no. 9, pp. 4025–4044, Feb. 2025, doi: 10.1007/s00170-024-13215-5.

[19] C. Favi and M. Marconi, "Product Eco-Design in the Era of the Circular Economy," *Sustainability*, vol. 17, no. 1, p. 213, Dec. 2024, doi: 10.3390/su17010213.

[20] W. Ahmed, V. Siva, J. Bäckstrand, N. Sarius, and H. Å. Sundberg, "Circular economy: Extending end-of-life strategies," *Sustain Prod Consum*, vol. 51, pp. 67–78, Nov. 2024, doi: 10.1016/j.spc.2024.09.003.

[21] I. Cukor Kirinić and M. Hegedić, "Trends and Future Research Direction of Lean Product Development," Dec. 01, 2023, *Multidisciplinary Digital Publishing Institute (MDPI)*. doi: 10.3390/su152416721.

[22] M. Madanchian and H. Taherdoost, "The impact of artificial intelligence on research efficiency," Jun. 01, 2025, *Elsevier B.V.* doi: 10.1016/j.rineng.2025.104743.

[23] S. Fukuda, A. Bernard, B. Gurumoorthy, and A. Bouras, "IFIP AICT 442 - Product Lifecycle Management for a Global Market."

[24] V. N. Kulkarni, V. N. Gaitonde, and B. B. Kotturshettar, *Product Lifecycle Management (PLM): A Key Enabler in Implementation of Industry 4.0*. Springer, Cham, 2021.

[25] A. J. Baptista, D. Peixoto, A. D. Ferreira, and J. P. Pereira, "Lean Design-for-X Methodology: Integrating Modular Design, Structural Optimization and Ecodesign in a Machine Tool Case Study," in *Procedia CIRP*, Elsevier B.V., 2018, pp. 722–727. doi: 10.1016/j.procir.2017.12.003.