UNIVERSITÉ DE STRASBOURG

École doctorale MSII (ED n°269)

Laboratoire des Sciences de l'Ingénieur, de l'Informatique et de l'Imagerie (ICUBE, UMR : 7357)

Equipe : Conception, Système d'Information et Processus Inventifs (CSIP)

THÈSE présentée par :

Rami GDOURA

Soutenue le : **11 Juin 2025**

Pour obtenir le grade de: **Docteur de l'Université de Strasbourg**

Discipline / Spécialité : **Génie Industriel/ Conception**

Contribution to the Integration of Lean into the Inventive Design of Manufacturing Systems in the Context of Industry 5.0

Contribution à l'Intégration du Lean dans la Conception Inventive des Systèmes Manufacturiers dans le Contexte de l'Industrie 5.0

THÈSE dirigée par :

M. HOUSSIN Rémy	MCF-HDR, Université de Strasbourg
Mme. DHOUIB Diala	Professeure, Université de Sfax

RAPPORTEURS :

M. MONTICOLO Davy	Professeur, Université de Lorraine
Mme. DERBEL Houda	Professeure, Université de Carthage

AUTRES MEMBRES DU JURY :

M. COULIBALY Amadou	MCF-HDR, INSA de Strasbourg
M. CHIBANE Hicham	MCF-HDR, INSA de Strasbourg
M. FRIKHA Ahmed	Professeur, Université de Sfax

Rami GDOURA

Contribution à l'Intégration du Lean dans la Conception Inventive des Systèmes Manufacturiers dans le Contexte de l'Industrie 5.0

Résumé

[1000 caractères maximum]

Cette recherche propose une méthodologie innovante et structurée pour l'intégration proactive des exigences du Lean et de l'Industrie 5.0 dès la phase de conception des systèmes manufacturiers. Elle s'articule autour d'une analyse approfondie des exigences et des paramètres, de la modélisation axiomatique et de la résolution inventive des contradictions, basée sur la théorie TRIZ.
Cette thèse constitue l'une des premières initiatives visant à formaliser le concept de Lean 5.0 et à intégrer de manière proactive ses exigences dès la conception. L'objectif est de fusionner les principes du Lean avec ceux de l'Industrie 5.0, afin de concevoir des systèmes atteignant les performances souhaitées dès leur conception, évitant ainsi des ajustements Lean a posteriori.
Cette recherche introduit une nouvelle approche de résolution de problèmes, ayant conduit au développement d'une méthodologie originale nommée "Lean 5.0 Parameter Integration Matrix", validée à travers un cas industriel concret en fabrication additive.
Elle explore également le potentiel de la combinaison entre des méthodes de conception routinières et inventives pour clarifier les éléments clés et répondre à la complexité de l'intégration simultanée des exigences du Lean et de l'Industrie 5.0.

Mots clés : Lean 5.0, Industrie 5.0, Durabilité, Résilience, Centrage sur l'humain, Conception des systèmes manufacturiers, Conception Inventive, Conception Axiomatique, TRIZ, Fabrication Additive

Abstract

[1000 caractères maximum]

This research proposes an innovative and structured methodology for the proactive integration of Lean and Industry 5.0 requirements from the early design phase of manufacturing systems. It is built around an in-depth analysis of requirements and parameters, axiomatic design modeling, and inventive contradiction resolution based on TRIZ theory.
This thesis represents one of the first initiatives aimed at formalizing the concept of Lean 5.0 and proactively integrating its requirements from the design stage. The objective is to merge Lean principles with those of Industry 5.0, in order to design systems that achieve the desired performance from the beginning, thereby avoiding post-design Lean adjustments.
This research introduces a novel problem-solving approach, which led to the development of an original methodology entitled "Lean 5.0 Parameter Integration Matrix", validated through a real-world industrial case study in additive manufacturing.
It also explores the potential of combining routine and inventive design methods to clarify key elements and address the complexity of simultaneously integrating Lean and Industry 5.0 requirements.

Keywords : Lean 5.0, Industry 5.0, Sustainability, Resilience, Human-Centricity, Manufacturing Systems Design, Inventive Design, Axiomatic Design, TRIZ, Additive Manufacturing

Acknowledgements

This Thesis stayed on track and got finished thanks to the support and encouragement of many people.

I want to express my sincere gratitude and thanks to my thesis supervisors, Prof. Rémy Houssin and Prof. Diala Dhouib, for their invaluable advice, guidance, and constant encouragement throughout this work. I also extend my thanks to my co-supervisor, Prof. Amadou Coulibaly, for his valuable assistance. Special appreciation goes to Prof. Hicham Chibane for his guidance and the expertise he shared in the field of inventive design.

I want to thank everyone who contributed to the success of this research, especially the members of the CSIP team at the ICUBE laboratory, University of Strasbourg, and the OLID Laboratory at the Higher Institute of Industrial Management, University of Sfax.

I would also like to thank the members of the jury for graciously accepting to evaluate this work.

Last but not least, I would like to express my profound gratitude to my parents. I am deeply thankful for their sacrifices, sincere encouragement, and unwavering support throughout my life. This thesis is the result of all the sacrifices they have made for my education.

“Limits are but illusions, walls we build in our own minds. Don't tell me what I can't do, for each obstacle is not a hindrance, but a teacher. In the face of adversity, we uncover our true potential. Every challenge we encounter is an invitation to evolve, to push beyond the boundaries of the self, and to grow in ways we never imagined. It is through struggle that the spirit is refined, and through perseverance that we transform our limitations into possibilities.”

Rami GDOURA

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Extended Word
AD	Axiomatic Design
AMS	Additive Manufacturing System
AP	Action Parameter
CM	Contradiction Matrix
DP	Design Parameter
EC	European Commission
EP	Evaluation Parameter
FBS	Function–Behaviour–Structure
FR	Functional Requirement
GSC	Generalized Solution Concept
I4.0	Industry 4.0
I5.0	Industry 5.0
L5.0PIM	Lean 5.0 Parameter Integration Matrix
LM	Lean Manufacturing
PC	Physical contradiction
PV	Process Variable
TC	Technical contradiction
TRIZ	Theory of Inventive Problem Solving

Chapter I: Introduction and Problem Statement

The industry's current approach to improving system performance by applying Lean tools during operational phases is curative. Many companies are implementing Lean tools in their manufacturing systems to achieve specific performance targets. This is often necessary because systems, as originally designed, are not always optimal and may contain unforeseen inefficiencies or wastage that were not taken into account during the design phase. As a result, it may be necessary to make some Lean interventions to enhance overall system performance. While this approach offers many advantages, it also encounters several significant limitations, which are central to this thesis. These limitations include constraints inherent in the design of existing manufacturing systems, which may not adapt to Lean-related changes, such as equipment limitations, the complexity of current processes and the resistance to change of employees accustomed to traditional procedures. In addition, significant investments in terms of time and cost are often required to implement Lean tools or integrate new technologies in order to overcome different constraints and wastes that may be avoided more simply by considering Lean requirements from the beginning. These adjustments can have an impact on the behavior of operators and their interactions with machines, leading to reduced cooperation and resistance to the new system.

Companies often fail to recognize the significance of implementing Lean tools until defects and waste manifest within the manufacturing process. We advocate for a shift in perspective, transitioning from a reactive or corrective approach to one that is proactive and preventive. This requires a redefinition of how Lean is viewed; rather than waiting for problems to emerge and then applying Lean as a solution, it should be adopted in a preventive manner. Essentially, adopting a preventive mindset for Lean integration means incorporating Lean tool requirements early in the design stages of the manufacturing system. By doing so, companies can align their processes with Lean principles from the beginning, focusing on preventing defects and waste rather than addressing them retroactively. This proactive strategy not only reduces the likelihood of issues arising but also enhances the efficiency of the entire production lifecycle.

To analyze and address this issue, this chapter aims to provide context and offer a general introduction to the thesis:

- Reception laboratories,

- Research problems positioning,

- General background of the thesis,

- Scientific problems and research questions,

- Structure of the manuscript.

1. Reception Laboratories (CSIP-ICUBE/OLID)

My thesis is carried out as part of a scientific collaboration between the CSIP team of the ICUBE laboratory at the University of Strasbourg and the OLID laboratory at the Higher Institute of Industrial Management of Sfax.

The main focus of the CSIP team is on inventive design and knowledge management, as well as the theoretical and practical development of new design methods for products, systems, and services that consider their entire lifecycle, particularly during the early stages of design. The OLID laboratory focuses on optimization, decision making, logistics, and business intelligence.

2. Research Positioning

Following the Lean movement, companies increasingly turn to modern technologies to enhance their performance by integrating advanced Industry 4.0 (I4.0) solutions. To merge Lean practices with I4.0, existing literature has introduced concepts such as Lean 4.0, Lean automation and smart Lean manufacturing.

As companies began to adopt I4.0 and explore the potential relationship between Lean practices and I4.0, the emergence of the Fifth Industrial Revolution followed. While I4.0 focuses primarily on enhancing the effectiveness and efficiency of manufacturing processes through a paradigm shift driven by new technologies, it has paid comparatively less attention to human and environmental factors. According to the (European Commission 2021), Industry 5.0 (I5.0) complements the I4.0 paradigm by aiming to design future systems that meet industrial and technological objectives while ensuring socio-economic and environmental sustainability. I5.0 is built upon three key pillars: Human-centricity, sustainability and resilience.

Lean can contribute to various performance criteria, either independently or in synergy with other concepts within the framework of I4.0 and I5.0, such as automation, flexibility and sustainability. Its integration from the design phase is broad, encompassing system components, flow design, and overall system behavior. However, ensuring that manufacturing systems are inherently aligned with Lean principles from the beginning remains a challenge. This thesis aims to develop a holistic design approach that enables designers to embed the desired performance characteristics from the early design phases by systematically integrating Lean requirements within the I5.0 context. Figure 1 shows the overall view of the thesis.

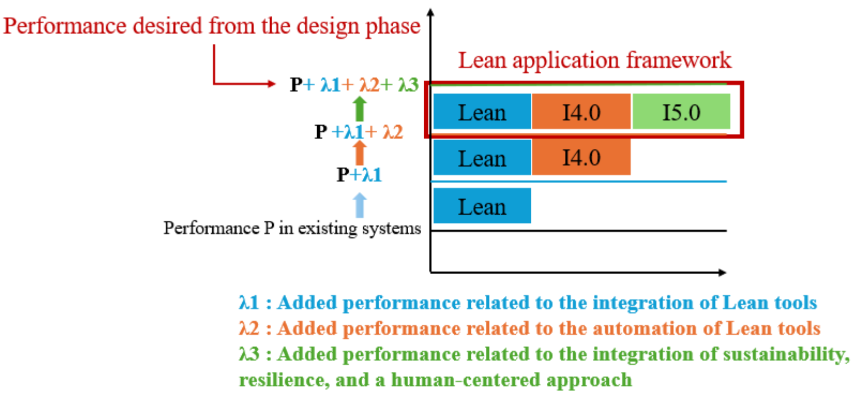

Figure 1: Overall View of the Thesis

By examining the synergies between Lean, I4.0, and I5.0 principles, we demonstrate how Lean has inherently aligned with the fundamental principles of I5.0 even before its official emergence. By integrating the technological advancements of I5.0 with classic Lean concepts that support its core values, our objective is to develop the Lean 5.0 paradigm integrating digital advancements with human-centric, sustainable, and resilient manufacturing practices.

A considerable number of studies in the literature emphasize the integration of diverse disciplines, concepts, and criteria during the design phase of manufacturing systems. This approach aims to address customer and user needs while minimizing the need for later modifications by incorporating additional procedures to enhance efficiency. A prominent example is the “Design for X” (DfX) methodology, where “X” denotes a particular objective that the system must achieve, such as maintenance, cost, safety, environmental considerations, and others.

Designing a high-performance manufacturing system necessitates the integration of various performance criteria, encompassing both traditional factors such as cost, productivity, quality and maintainability, as well as more recent criteria that have gained significance with the advent of the I5.0 concept. These emerging criteria fall under the overarching themes of sustainability, resilience and human-centricity.

In our research, we propose the “Design for Lean 5.0” concept, which seeks to address the limitations of traditional DfX methodologies by combining the diverse performance criteria these methodologies emphasize. The approach we propose integrates Lean requirements to satisfy these criteria while aligning them with the principles of I5.0. In this context, we propose a new perspective that frames Lean requirements as the gap between the current undesirable state (or the state that must be identified in the design of a new system) and the optimal, performance-driven operations that adhere to Lean principles for the design of future systems. We propose a systematic approach designed to overcome the limitations of Lean applications in current systems, focusing on the design of systems that inherently incorporate the necessary requirements. This approach eliminates the need for reliance on traditional Lean tools in future system designs. Additionally, it empowers companies to achieve more efficient, self-sustaining systems without relying on extensive Lean interventions, while integrating I5.0 principles and technologies.

We examine the limitations of Lean Tool applications in current systems and propose strategies for mitigating them during the design phase of manufacturing systems. Our approach advocates a shift from a reactive, corrective mindset to a proactive, preventive one. By addressing the existing challenges proactively from the beginning, we aim to formulate and integrate several Lean tool requirements in an I5.0 context to design a Leanless (Minimal Lean application required) sustainable, adaptable systems with minimal waste and human-centered considerations.

While integrating Lean and I5.0 requirements during the design phase is important, the process of combining and integrating multiple requirements and their associated parameters can lead to a complex system, sometimes resulting in contradictions. To address this complexity, we chose to use the Axiomatic Design method to decompose the initial complex problem, propose independent solutions for the integration of requirements, identify the corresponding parameters and outline the mechanisms and tools for its integration.

Additionally, we propose a methodology based on TRIZ theory, which enables the identification and resolution of contradictions that may arise from the resulting parameters early in the design phase, preventing any negative impact on the overall system's performance.

Figure 2 summarizes the methods used in our methodology and their utility.

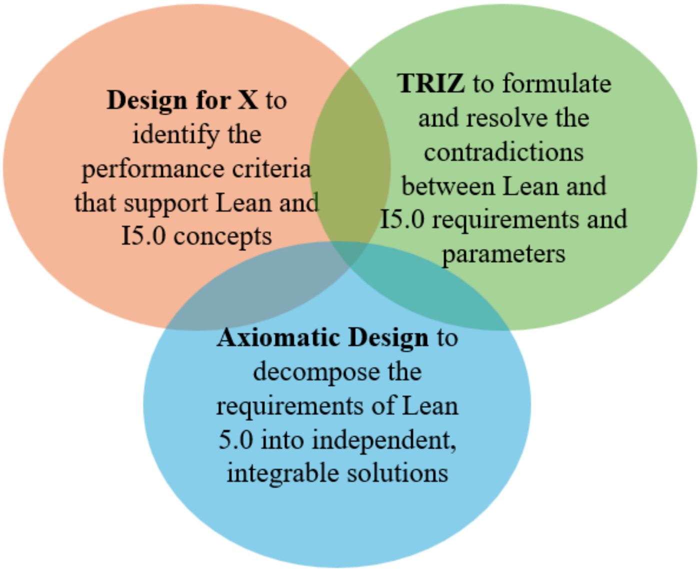

Figure 2: Methods Applied in Our Methodology

In summary, this thesis examines the complementary relationship between Lean, I4.0, and I5.0, leading to the introduction of the Lean 5.0 paradigm. We propose a methodology that empowers designers to design inventive manufacturing systems that meet desired performance criteria from the beginning. Additionally, we develop a Lean 5.0 Axiomatic model, which incorporates Lean requirements aligned with I5.0 principles into the system design. Finally, we address and resolve potential contradictions arising from this integration.

3. General Background of the Thesis

Lean production is a concept focused on optimizing processes to minimize waste and maximize resource utilization. It is evolved from the Toyota Production System (TPS) and has since become widely recognized as an effective practice for manufacturing companies globally. The success and popularity of Lean in enhancing productivity and promoting competition have led to its adoption in various non-manufacturing sectors. In the following sections, we introduce the Lean concept, along with its core principles and tools.

3.1 Lean Thinking: Concept and Tools

Lean Thinking is a management philosophy concerned with the integration of individuals in manufacturing processes, with an emphasis on value-added activities for customers by reducing waste and producing exactly what is required, in the right time (Perico and Mattioli 2020).

The term “Lean”, originally defined as a “Lean production system”, has undergone significant evolution since the introduction of the Lean production concept in 1988. This progression continued with the emergence of the Lean 4.0 concept in 2017, and there are now some initiatives, including our research, aimed at introducing the Lean 5.0 concept.

Lean Manufacturing (LM) is a production philosophy focused on the elimination of waste while enhancing customer value. Essentially, Lean aims to use fewer resources to deliver more value, emphasizing process stability, product quality and respect for workers (Ohno 1988).

The key principles of LM, as outlined by (Womack and Jones 1997), focus on improving efficiency and value within the production process. These principles include the elimination of waste at every stage, the integration of quality directly into the production process, and the reduction of costs by optimizing resource use. Additionally, Lean emphasizes the development and implementation of tools that enhance the functional performance of the organization, ensuring that all processes contribute to greater value creation.

LM is an integrated manufacturing strategy with an emphasis on maximizing capacity and minimizing system variability. The goal is to create the highest product value for the customer while using the fewest resources possible to design, build, and sustain the product (Anvari et al. 2014).

The TPS is built upon two foundational concepts: “Just in Time (JIT)”, which ensures that each process produces only what is needed by the subsequent process in a continuous flow and “Automation with a Human Touch (Jidoka)”, which dictates that when a problem occurs, the machine or process halts immediately to prevent the production of defective products. Figure 3 illustrates the two pillars, JIT and Jidoka, that support and integrate the entire system, with a robust foundation aimed at achieving the key objectives placed on the roof.

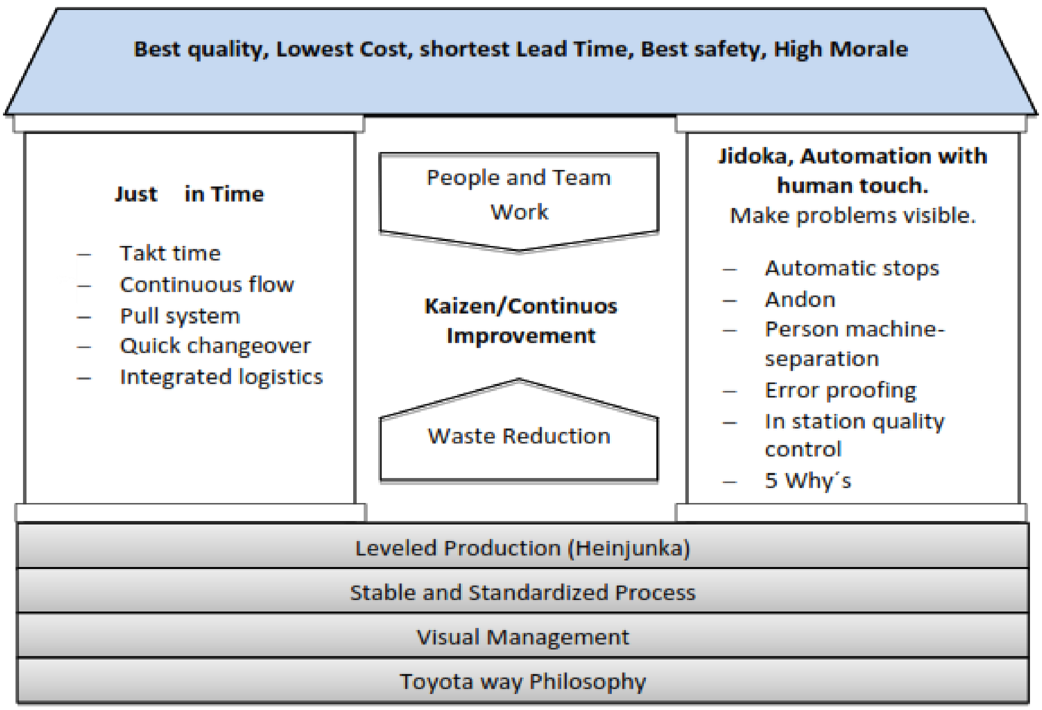

Figure 3: Temple of Toyota Production System

(Ohno 1982) identify seven forms of waste (Muda): overproduction, waiting time, transportation, storage, unnecessary movement, and the production of defective parts. In addition, two other types of waste were identified:

- Muri: Physical overload, excessive strain, mental stress, etc.
- Mura: Irregularity, inconsistency, lack of uniformity, etc.

When TPS was adopted in Europe, the workers' non-utilized talents and skills were introduced as the eighth waste of Lean as shown in Figure 4.

Figure 4: 8 Wastes of Lean

Lean is defined as a process comprising five key steps: the first involves defining customer value, followed by defining the value stream, ensuring a continuous flow, establishing a pull-based system, and finally, striving for perfection (Gupta and Jain 2013). Lean thinking, rooted in the TPS, serves as a structured approach to define value, organize value-creating activities in the most effective sequence, execute them in a continuous manner based on customer demand, and do so with maximum efficiency. The five core principles of Lean thinking are illustrated in Figure 5.

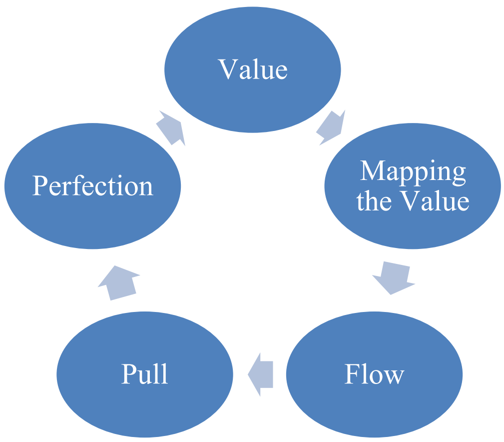

Figure 5: Principles of Lean Thinking

Lean is based on a set of tools and practices that an organization may use as needed. Two categories may be used to classify LM tools:

- Tools aimed to simplify individual operations, such as 5S, SMED (Single Minute Exchange of Die), TPM (Total Productive Maintenance), etc.

- Tools for improving physical flow such as Value Stream Mapping (VSM), Kanban, etc

(Anvari et al. 2014) identify the following Lean tools: Andon, Heijunka, Hoshin-Kanri, Five why, Jidoka/automation, JIT, Kaizen/Continuous improvement, Kanban, one-piece flow, point-of-use storage, Poka- yoke, SMED/quick changeover, standardized work, Takt time, TPM, visual factory, VSM, and workplace organization/5S.

When designing a new manufacturing system, determining the appropriate set of Lean tools to integrate during the early design phases can be challenging. At this stage, detailed information about equipment and production flows is often unavailable. Lean encompasses a wide range of tools and methods, most of which are typically implemented in existing systems. Their effectiveness is generally assessed through collected data, such as production cycle time analysis, defect rate measurement, and inventory level tracking.

In the following, we outline the LM methods and tools that form the basis of our discussion in the subsequent chapters. According to our analysis, these tools can be proactively integrated from the design phase and have a strong connection with I5.0 principles. The selected tools are: JIT, Kanban, Poka-Yoke, VSM, TPM, Heijunka, 5S, and SMED.

❖ **Just In Time (JIT)**

JIT/ Just-in-Sequence (JIS) is a Lean method designed to ensure the delivery of the right product, at the right time, place, and quality, in the correct quantity, and at an optimal cost. As one of the foundational pillars of the TPS, JIT focuses on producing only what is needed, precisely when and where it is needed, and in the exact amount required. Unlike traditional production processes, JIT advances production through the supply chain by utilizing resources only when they are required for the next operation. From a system-wide perspective, JIT offers significant advantages by minimizing issues related to overproduction, transportation inefficiencies, extended lead times, unnecessary resource movement, and product defects (Mayr et al. 2018).

❖ **Kanban**

The Kanban method is an information-based control system that manages production quantities at each stage of the operation. Its primary objective is to initiate the pulling of parts only when needed, while also enabling the visualization and regulation of in-process inventories (Matzka et al. 2012). At any stage, the Kanban system is capable of maintaining a minimum stock level. It functions by capturing essential information related to the actual production flow, while simultaneously enabling the smooth movement of processes and materials. This is achieved through the use of cards, which represent a structured sequence of orders and resources distributed across the production floor (Kolberg and Zühlke 2015). Kanban helps to decentralize control and limit Work in Process (WIP) by managing and streamlining the flow of materials and parts in job shops. It regulates the movement of parts between workshops, controls the flow between machines, and oversees batch sizes and inventory levels (Junior and Godinho Filho 2010).

- **Poka-Yoke**

Poka-Yoke mechanisms help to detect and eliminate abnormal conditions in production processes, thus preventing the creation of defective products. This LM tool generates forced sequences in production lines and examines processes as they run, stopping them in the event of errors and founded problems. Poka-Yoke devices are designed to automatically halt the manufacturing line when necessary, as well as to prevent and detect losses from various sources, such as defects, misalignments, or incorrect inputs. These devices incorporate mechanisms that guide operators to perform tasks correctly, such as sensors that verify the proper assembly of parts. Additionally, these devices provide real-time feedback or trigger alarms when deviations from standard processes occur, helping to maintain process integrity and reduce errors (Valamede and Akkari 2020).

- **Value Stream Mapping (VSM)**

VSM enables the identification and visualization of all actions along the production line, including both value-added and non-value-added activities. It's based on a visual representation of the flow that offers a thorough process analysis that permeates several levels of a production structure. This analysis is used to minimize Lead times and costs, simplify work processes, remove waste, and improve productivity and quality (Wagner et al. 2017).

- **Total Productive Maintenance (TPM)**

TPM is a comprehensive set of techniques designed to ensure that each machine within a production process consistently performs its designated functions. The primary objective of this approach is to enhance both productivity and quality, while simultaneously motivating employees and improving job satisfaction. TPM employs an innovative maintenance strategy that focuses on maximizing equipment efficiency, preventing breakdowns, and encouraging autonomous maintenance by operators through routine activities involving the entire workforce (Singh et al. 2013). TPM aims to maximize equipment effectiveness by optimizing availability, performance, efficiency, and product quality. It involves establishing a preventive maintenance strategy that covers the entire life cycle of the equipment. The approach requires collaboration across all departments, including planning, user, and maintenance teams, to ensure comprehensive involvement in the maintenance process. Additionally, TPM engages all staff members, from top management to shop-floor workers, encouraging improved maintenance practices through small-group autonomous activities (Ahuja and Khamba 2008). The eight pillars for the success of TPM implementation are shown in Figure 6.

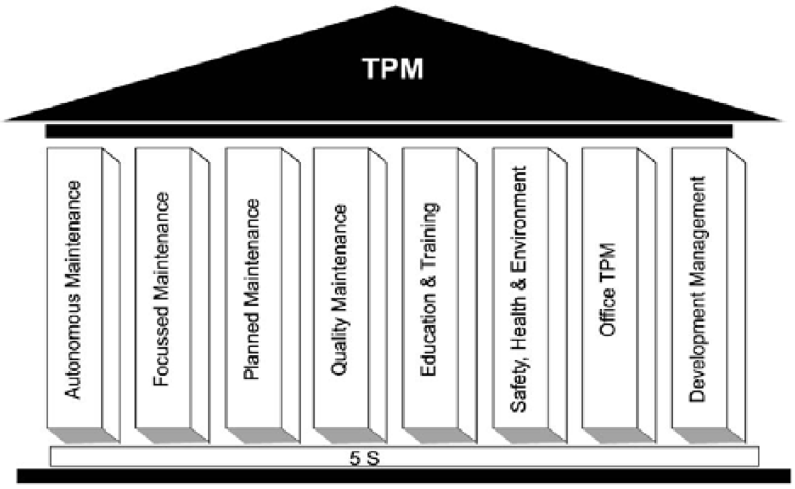

Figure 6: Pillars of TPM (Singh et al. 2013)

- **Heijunka**

The objective of Heijunka (also referred to as leveling the production schedule) is to avoid peaks and valleys in the production schedule, it proposes distributing the jobs that require more worker input throughout the production schedule to allow for higher average utilization, assuming that the cycle time remains constant over time (Hüttmeir et al. 2009). Heijunka incorporates the concepts of leveling and line balancing; it corresponds to the effort to balance the workload with the process's capacity or capability, which includes the capacities of the machines and the operators. Build-to-order and build-to-stock companies sometimes create large volumes in one week, paying overtime and taxing employees and equipment, and then send staff members home the next week due to decreased orders (Matzka et al. 2012). Heijunka improves operational stability, reduces variability in resource utilization and material requirements, and minimizes quality issues, breakdowns, and defects (Kjellsen et al. 2021).

- **5S**

The 5S methodology is instrumental in minimizing non-value-adding time, boosting productivity, and enhancing quality. It is a tool aimed at dismissing time waste, organizing and improving the workplace and preventing accidents with norms and standards. The 5S are Seiri, Seiton, Seiso, Seiketsu, and Shitsuke (classification, organization, cleaning, standardization and improvement). First, “Sort” involves organizing items for easy storage and retrieval. Next, “Set” designates specific places for everything, clearly labeling storage areas to eliminate unnecessary searching. “Shine” focuses on maintaining cleanliness and ensuring all tools and equipment are well-kept. “Standardize” emphasizes the documentation of consistent work methods to streamline operations. Finally, “Sustain” encourages the development of a habit of continuous improvement through consistent adherence to these procedures. Together, these steps create a structured and efficient environment that promotes long-term operational success (Omogbai and Salonitis 2017).

Several authors have adopted the 6S methodology, an extension of the traditional 5S method (Sort, Set in order, Sweep, Standardize, Sustain), with the addition of Safety, as a foundational framework for all improvement initiatives. This approach supports waste reduction, promotes a cleaner and safer working environment, minimizes non-value-added time, enhances work efficiency, and improves the visual organization and clarity of the workplace (Sá et al. 2021).

❖ **Single Minute Exchange of Die (SMED)**

SMED is a well-known Lean method for reducing the time needed to complete an equipment changeover, often to less than 10 minutes. Some companies have even achieved set-up times of less than a minute, implementing the evolution of SMED, one-touch die exchange (OTED). Taking this concept to the extreme, it is possible to adopt the NOTED (Non-Touch Exchange of Die) approach (Braglia et al. 2023). SMED focuses on reducing changeover time by distinguishing between different types of preparation activities. It categorizes all tasks into internal and external activities. Internal activities require the machine to be stopped, whereas external activities can be carried out while the machine is still operating. The core principle of SMED is to shift as many activities as possible to the external category, thereby minimizing machine downtime and improving overall production efficiency (García-Alcaraz et al. 2021).

While this section highlighted the core Lean tools and their potential to optimize manufacturing processes, it is equally important to explore the limitations and challenges associated with their application. In the following section, we explore these limitations.

3.2 Lean Application Limitations

Our aim is to propose a new concept that integrates Lean tools from the design phase while overcoming the constraints and limitations of their implementation in existing systems. For this reason, we analyze these limitations to be taken into account to design the future system. (Qureshi et al. 2023) classify Lean practices into two categories:

- Soft Lean practices include Small-group problem solving, Worker empowerment, Multi-skilling development, Customer relationship management, Customer focus, Training employees, Organizational culture, Supplier development and partnership, Total employee involvement, Top management leadership, and Continuous improvement.

- Hard Lean practices including Total quality management, TPM, Just-in-time delivery by the supplier, Production scheduling and systemization, Statistical process control, Kanban Setup, Setup time reduction, Equipment layout for continuous flow, Autonomous maintenance and LM Practices.

The soft part of Lean practices had much more intention in the literature to study their limitations in existing production systems. According to (Almeida Marodin and Saurin 2015), the barriers to implementing Lean production within an existing system are predominantly associated with social and managerial challenges. One of the most common obstacles is employee resistance, which may stem from fear of change, lack of understanding of Lean principles, or concerns about job security. These human factors can significantly hinder the successful adoption and integration of Lean practices. (Kleszcz 2018) identify 7 barriers and limitations occurring during the implementation of LM: lack of infrastructure, lack of understanding, lack of visible benefits, lack of communication, unintelligible measures, fear of change and lack of knowledge. (Chaple et al. 2021) resume the barriers of Lean implementation in 10 main points: Insufficient investment cost, insufficient internal funding, insufficient supervisory skills, insufficient management time, insufficient workforce skills, insufficient senior management skills, insufficient external funding, employee attitudes or resistance to change, cultural issues and insufficient understanding of the potential benefits.

The works mentioned above resume the majority of the limits and barriers found in the literature. However, there is a lack of works that address hard Lean practices and technical limitations of Lean manufacturing tools implementation into existing systems. For these reasons, we identify these technical limitations in the aim to suggest some ideas for overcoming these limitations by proposing a set of Lean functional requirements that will guide us in the elaboration of the Lean 5.0 Axiomatic model.

Effective methods for analyzing, understanding, and systematically resolving these challenges are essential for designing systems that overcome limitations and achieve the desired performance. Such methods streamline the process by quickly identifying issues, implementing appropriate solutions and preventing costly design mistakes. In the following, we present some of these methods, with a focus on those that will be used in our proposed methodology.

3.3 Design methods

Engineering design can be thought of as an activity that benefits society by promoting the development of new products and systems to meet the requirements and aspirations of society. A multifaceted, complex discipline encompasses many different features and knowledge from numerous scientific sciences (Souchkov 1998). In the realm of design, the complexity and challenges associated with different stages can vary significantly. The design process often unfolds in multiple stages, each with its own set of characteristics and difficulties. The three key stages commonly recognized are adaptive design, developed design, and new design (Haik and Shahin 2011).

- **Adaptive Design:** In the majority of cases, designers primarily engage in adapting existing designs. In certain manufacturing sectors where development has nearly halted, the designer's role often boils down to making minor adjustments, typically in the dimensions of the product/system. This type of design work requires no specialized knowledge or extraordinary skills, as designers with basic technical training can effectively address the relatively straightforward problems encountered.
- **Development Design:** Development design demands a higher level of scientific training and design proficiency. Designers in this phase commence with an existing design as a foundation, but the end result may exhibit significant deviations from the original product/system. The complexity lies in the necessity for a deeper understanding of underlying principles and more intricate problem-solving skills compared to adaptive design.
- **New Design:** New design represents a select category, and it is arguably the most challenging level. Creating an entirely new concept goes beyond the realms of adaptation and development. Designers at this stage must not only possess technical expertise but also wield creativity, imagination, insight, and foresight. Generating innovative ideas necessitates mastery of all the skills acquired in the earlier stages, making new design the pinnacle of design complexity.

All forms of the systematic design process mentioned in the literature revolve around the same following fundamental stages: Planning and Clarifying the Task/ Requirements Specification, Concept Design, Embodiment Design and Detailed Design (Pahl et al. 2007).

- Planning and Clarifying the Task: Leads to a product idea that is needed and appears to be promising in light of the existing market situation, company needs, and economic outlook. Before launching a product development project, the idea must be established.
- Concept Design: Description of the form, function and features of a product, into two consecutive components: (1) Concept Generation and (2) Concept Screening and Improvement.
- Embodiment Design: Defines the arrangement of assemblies, components and parts, as well as their geometrical shape, dimensions and materials.
- Detailed Design: All of the individual parts' arrangements, forms, dimensions, and surface properties are finally defined, materials are specified, production possibilities are assessed, costs are estimated, and all drawings and other production documents are developed (Hasenkamp 2010).

When designing a new system, a problem is being solved. Many effective design methodologies and processes are used to assist the designer in considering various performance criteria. These methodologies can be categorized into two types: First, the routine problem-solving methods, which focus on analyzing the root causes of a problem and applying known and standard solutions. Second, inventive problem-solving methods which encourage invention by utilizing principles and models to change the existing model and generate new and original ideas (Abdellatif et al. 2024).

Utilizing routine methods to find solutions can be effective in many situations and for various problems. However, this approach falls short when addressing inventive problems that necessitate the introduction of new variables and the establishment of novel relationships among them. Routine methods typically explore potential solutions within the confines of the defined problem space, which limits the likelihood of discovering a comprehensive global solution. Some examples on the routine methods are: Design for X (DfX), Functional analysis, Plan–Do–Check–Act (PDCA) cycle, DMAIC (Define, Measure, Analyze, Improve, and Control), DMADV (Define, Measure, Analyze, Design, and Verify), morphological matrices, Quality Function Deployment (QFD), etc. Some inventive methods are based on TRIZ theory (Theory of Inventive Problem Solving) and others non based on TRIZ. Some examples of the non-TRIZ-based methods used for inventive process are: Concept-Knowledge (C-K) theory, Axiomatic Design (AD), Function–Behaviour–Structure (FBS) Framework (Abdellatif et al. 2024).

In developing the Lean 5.0 model, we selected AD over alternative methodologies like QFD and Design for Six Sigma (DFSS) due to its superior ability to handle system-level complexity and socio-technical integration. While QFD effectively translates customer needs into technical specifications and DFSS optimizes product/process quality through statistical rigor, both methods are limited to incremental improvements within predefined product or process boundaries. Lean 5.0, however, demands a holistic framework that harmonizes Lean's operational efficiency with I5.0's human-centricity, sustainability, and resilience, which represent a challenge requiring systematic decomposition of interdependent requirements without trade-offs.

In this thesis, we integrate both routine and inventive design approaches. Specifically, we use the DfX methodologies to identify design objectives applicable to different system design, serving as a guide for defining requirements and parameters. Moreover, the focus would be more on the decomposition of the complex problem of designing a Lean 5.0 System, by extracting the most important problem to be solved, particularly through the combination of TRIZ and AD. (Shirwaiker and Okudan 2008) highlight the effectiveness of both TRIZ and AD in solving industrial problems, each with its own strengths. TRIZ excels in generating innovative solutions by resolving contradictions, whereas AD focuses on systematically defining and analyzing problems based on its two axioms. While AD provides a structured framework for problem definition, it lacks specific techniques for solution generation. Conversely, TRIZ is highly effective in finding creative solutions but may struggle with complex, multi-variable problems. AD is widely applied in structuring manufacturing systems, while TRIZ is commonly used for optimizing product design and manufacturing processes. Given their complementary nature, integrating AD and TRIZ provides a more robust approach, combining systematic problem structuring with inventive solution generation.

The FBS framework, proposed by Gero in 1990 (Gero and Kannengiesser 2004), divides the design process into three main elements: Function (F), which defines what the system is intended to accomplish; Behavior (B), which describes how the system operates to fulfill its function; and Structure (S), which consists of the physical or logical components that form the system. This type of framework assumes that function and structure are interconnected through behaviour, which represents the actions performed to accomplish a given function and illustrates how the structure supports the realization of that function (Tao et al. 2019).

The integration of TRIZ and AD offers significant potential for enhancing the engineering design process; however, to fully leverage their combined strengths, the adoption of the FBS framework could be useful. FBS serves as a bridge between TRIZ and AD by clearly illustrating how structural changes (introduced through TRIZ) impact system behavior, and how those behaviors, in turn, fulfill the intended functions defined by AD. This alignment ensures that inventive solutions are systematically connected to functional objectives.

4. Scientific Problems and Research Questions

Our aim is to enhance manufacturing efficiency, adaptability, and sustainability by integrating Lean and I5.0 principles from the design phase of manufacturing systems. Traditional Lean methodologies focus on waste reduction, process optimization, and value creation, while I5.0 emphasizes sustainability, resilience, and the synergy between advanced technologies and human expertise. The challenge lies in bridging these two paradigms to propose a new approach that leverages smart technologies while preserving Lean’s efficiency-driven philosophy.

To achieve this objective, we propose Lean 5.0 as a framework that aligns Lean methods and tools with I5.0 principles, ensuring that digital transformation and automation enhance human and environmental considerations while improving the adaptability of manufacturing systems. Additionally, we formulate and integrate Lean 5.0 requirements to design intelligent, flexible, and sustainable manufacturing systems that respond dynamically to market demands while maintaining high efficiency and operational excellence.

Based on our objective, the following research questions arise:

1. Can the Lean requirements be considered from the design phase?
2. What is the interdependence between Lean, I4.0, and I5.0, and how does it influence the evolution of manufacturing systems?
3. Are Lean tool requirements adapted to the I5.0 context?
4. What design methodologies can facilitate the integration of Lean and I5.0 from the design phase?
5. What are the limitations of applying Lean tools in existing systems?
6. How to formulate a Lean requirement?
7. How can we assist designers in maintaining Leanless performance of the system?
8. How resolve the complexity of integrating Lean requirements from the design phase in an I5.0 context?
9. What are the Lean 5.0 requirements that can be considered from the design phase?
10. How to solve the contradictions due to the integration of various Lean and I5.0 requirements from the design phases?

As we began our research on the proactive integration of Lean requirements from the design phase of manufacturing systems, our initial focus was to assess the feasibility of aligning this integration with the concept of I4.0. We developed a framework aimed at enhancing system performance by integrating Lean tools with I4.0 technologies into the design of manufacturing systems. Furthermore, we provided empirical evidence, based on a questionnaire survey supported by exploratory and confirmatory factor analysis, that demonstrates the impact of incorporating Lean 4.0 tools during the design phase across five critical design dimensions. The full details of this contribution are published in (Gdoura et al. 2024a), which can be considered one of the first contributions to address this topic. It builds upon the work of (Slim et al. 2021a), which proposes a framework for integrating Lean functionalities from the design phase. This part represents the starting point of our PhD research, establishing a foundation for further exploration and development toward modeling and integrating Lean 5.0 concept.

Building on our initial contribution, which focused on integrating Lean 4.0 from the design phase and evaluating its impact on manufacturing systems performance, our ongoing research has revealed several limitations within the Lean 4.0 framework. Furthermore, with the emergence of I5.0 and its increasing influence on the future of manufacturing systems, incorporating its principles has become essential for the next generation of systems design.

5. Manuscript Structure

To answer to the research questions, we present in the following the scope of this thesis:

Chapter II: State of the Art on Lean and Industry 5.0 Integration into Manufacturing Systems Design

To answer the first question regarding the consideration of Lean requirements from the design phase, we conduct a literature review on the integration of Lean principles to improve both the design process and the performance of the resulting system.

To answer the second and the third questions regarding the interdependence between Lean, I4.0, and I5.0, we first analyze the transition from I4.0 to I5.0 and identify the I5.0 principles that address the limitations of I4.0. Next, we conduct a literature review to examine how I5.0 principles can be considered from the design phase. We then explore the combination of Lean and I4.0, which has led to concepts such as Lean 4.0, and analyze the integration of this concept from the design phase, highlighting its limitations. This analysis guides us in exploring the combination of Lean with I5.0. We further review the synergy between these two concepts across two timeframes: after the official announcement of I5.0, focusing on the synergy between the two concepts, and before the official announcement of I5.0, examining the synergies between Lean and I5.0 fundamental principles. Finally, we conduct a literature review to assess the integration of both concepts from the design phase.

To answer the fourth question regarding the design methodologies that facilitate the integration of Lean and I5.0 from the design phase, we first conduct a literature review of 34 Design for X (DfX) methodologies to identify the relevant performance criteria encompassing both Lean and I5.0 principles. Next, we review the Axiomatic Design (AD) method and examined previous works that have applied this method to model Lean and I5.0 principles. Finally, we analyze the complementarity between Lean and TRIZ, exploring how this synergy contributes to facilitating the integration of Lean tools and functionalities into the design of manufacturing systems by addressing potential contradictions.

Chapter II concludes by summarizing eight gaps identified in the literature, along with our contributions aimed at addressing these gaps.

Chapter III: A New Methodology for Inventive Lean 5.0 Manufacturing Systems Design

In this chapter we present our global methodology for developing and integrating Lean 5.0 from the design phase of manufacturing systems using AD and TRIZ methodologies.

To answer questions 5, 6, and 7, which focus on identifying the limitations of Lean tool applications, formulating Lean requirements, and designing a Lean-driven performance for systems, we begin by extracting Lean requirements and their corresponding evaluation parameters within the I5.0 context, as derived from the literature. These serve as guidelines for designers to integrate these requirements and ensure their system's performance aligns with them. Next, we analyze the limitations of Lean tool applications in existing systems and derive the Lean functional requirements to be integrated during the design phase, aiming to minimize the need for Lean interventions in future system designs.

To answer questions 8 and 9, we use the AD Method to propose a generalized Axiomatic Model for Lean 5.0 manufacturing systems. This model offers independent, integrable solutions that combine Lean tool requirements with the principles of I5.0. Each solution consists of a Lean tool's functional requirement combined with an I5.0 principle, its corresponding design parameter, and the related process variable.

Chapter IV: A New TRIZ-based Approach for Designing Inventive Manufacturing Systems

To answer question 10, we draw on inventive design principles from TRIZ theory to propose a new methodology called the "Lean 5.0 Parameter Integration Matrix (L5.0PIM)". This methodology assists designers in identifying and resolving contradictions that arise from the integration of multiple performance parameters, guiding them toward inventive solutions.

Chapter V: Application of L5.0PIM in Additive Manufacturing Systems: Case Study

In this chapter, we apply the L5.0PIM methodology to improve the performance of additive manufacturing systems in prototyping a Handiski Knee Prosthesis, exploiting the results of the Lean 5.0 Axiomatic model. We identify various contradictions related to the improvement of the current process and propose inventive solutions to resolve them through the integration of Collaborative Robot (Cobot).

A thesis plan illustrated in Figure 7 expose the progress of our scientific approach.

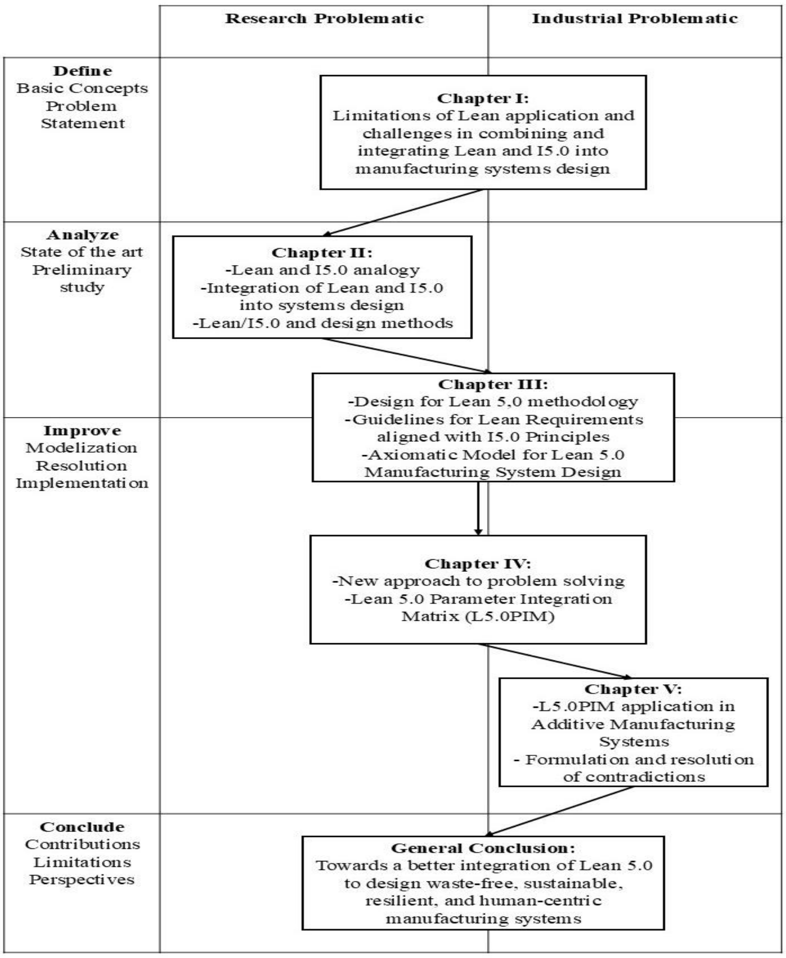

Figure 7: Thesis Plan

Chapter II: State of the Art on Lean and Industry 5.0 Integration into Manufacturing Systems Design

Introduction

In this thesis, we aim to integrate Lean requirements from the design phase to ensure alignment with Industry 5.0 (I5.0) criteria and orientations, enhancing the performance of manufacturing systems while minimizing reliance on Lean tools and methods during the operational phase. To achieve this, we conduct a comprehensive literature review to analyze the interdependence between Lean, Industry 4.0 (I4.0), and I5.0, as well as their combinations and integration from the design stage. We introduce I4.0 to highlight its impact on system performance and discuss its limitations, which have led to the emergence of I5.0. Additionally, we present the key conceptual approaches defining these two paradigms, their core technologies, and the fundamental differences between them, while examining their integration into system design.

Furthermore, we explore the incorporation of Lean and Lean 4.0 into the design phase to enhance system performance and analyze the synergy between Lean and I5.0 and their implications for system design. We also review various studies that have employed the Axiomatic Design method to develop systems or models for integrating Lean and I5.0 principles. Moreover, we investigate the combination of Lean with the TRIZ method. For each aspect, we conduct an analysis of existing research to identify the gaps in the current literature.

1. Integration of Lean into Systems Design

The integration of Lean into the design phase can be approached in two distinct ways: one focuses on enhancing the design process itself, while the other aims to improve the overall performance of the manufacturing system being designed. The first approach applies Lean principles to streamline design activities, reduce inefficiencies, and accelerate product and system development, ensuring a more effective and waste-free design process. The second approach, however, seeks to embed Lean principles directly into the system architecture, designing manufacturing systems that inherently minimize waste, optimize flow, and require fewer post-design interventions. While both perspectives contribute to operational efficiency, the latter remains less explored in research, despite its potential to fundamentally transform manufacturing systems by integrating Lean requirements from the earliest design stages. In the following, we explore these two approaches.

1.1 Lean to Improve the Design Process

Many design methods based on Lean have been developed to help designers to satisfy the constraints and requirements related to the design process. The majority of those methods are following Lean thinking.

Traditional Lean applications in design have primarily focused on optimizing the design process itself. Notable examples are in the following.

One of the common design methods related to Lean is called Lean Design which is a further technique that is effectively applied throughout the design process. It arose from the foundational notion of Lean Thinking, which is to focus on activities that add value to the end customer; this method consists on the elimination of all non-value-added operations in design process. Lean design is based on the idea that product life cycle processes should not be optimized directly, but rather through product design. As a result, Lean Design aims to improve process efficiency, but from the standpoint of better product design (Dombrowski et al. 2014).

Lean Product Development (LPD) is one of the most popular methods for maximizing value, improving quality, reducing lead times, and lowering costs in Product Development (PD) processes. (León and Farris 2011) identify the framework of LPD:

- Lean design techniques to do a better job faster with less effort.
- LPD techniques to develop product faster with less effort.
- LPD subsystems to provide a systematic view of the TPS for PD.
- LPD principles to generate profitable operational value streams in a predictable, effective, and efficient manner by leveraging actionable and applicable knowledge throughout the development process.

(Womack et al. 1991) identifies four key characteristics of the Lean concept in the LPD framework: leadership, teamwork, communication, and simultaneous development. LPD, according to (Hoppmann et al. 2011), is structured around five core principles: a strong emphasis on value creation, the empowerment of system designers as entrepreneurial leaders, the implementation of concurrent engineering practices, the establishment of development rhythm through cadence, flow, and pull mechanisms, and the formation of accountable expert teams to drive performance and innovation.

Lean Production Development applies Lean principles to the product development process, aiming to enhance efficiency by reducing lead times, lowering costs, and improving quality through structured engineering and organizational practices inspired by Toyota. It emphasizes balancing conflicting objectives and relies heavily on effective knowledge management to support continuous improvement and innovation (Canonico et al. 2022).

Design for Six Sigma (DFSS) is a method that describes how to apply the steps of the Six Sigma technique to the engineering design process. DFSS aims to better meet customer requests and expectations by decreasing faults and inconsistencies in existing goods and focusing on a thorough grasp of the client's needs to produce a new, more satisfying, and inventive product/system (Liverani et al. 2019).

(Baptista et al. 2018) propose the Lean Design-for-X (LDfX) approach by adhering to the LPD and Modular Design concepts, LDFX were intended to provide consistent decision help for comparing various design concepts or products that use various “X” domains.

(Rauch et al. 2016) present the new intelligent PD approach, which combines the principles of Lean and I4.0 with LPD. I4.0 offers numerous opportunities for Smart Product Development (SPD) through the introduction of advanced computing platforms and new technologies. (Nunes et al. 2017) highlight the primary advantages of combining physical and virtual or augmented prototyping in SPD. They also address other critical factors that need consideration during SPD processes, such as cost management, human factors, and the integration of I4.0 methodologies with Lean Production.

The approaches discussed primarily concentrate on improving efficiency, minimizing waste, and streamlining the development process. However, there is limited research on how to integrate Lean principles to enhance the overall performance of designed systems, especially in designing systems that naturally require minimal Lean intervention during their operation. Most existing studies focus on refining the design process and optimizing the utilization of current production systems. This leads us to identify a significant gap:

- *First Gap: The focus of integrating Lean into the design is on improving the design process itself, with limited research on the integration of Lean to enhance the designed system that is the subject of the design process.*

1.2 Lean to Improve the Performance of Designed Manufacturing Systems

Many companies employ Lean principles and tools to improve their manufacturing processes in order to meet certain performance goals. They do so since developed systems aren't always perfect and occasionally require tweaking to improve their performance. Integrating Lean principles from the design phase has the potential to emerge as a highly effective strategy for improving the overall performance of a system and optimizing the interrelationships between its various components.

The work of (Slim et al. 2018; Slim et al. 2021a; Slim et al. 2021b) can be seen as a first exploration of Lean requirements in the early phases of design. Their approach to incorporating Lean requirements is based on the integration of Lean criteria and functionalities, highlighting how this integration can support the development of I4.0. One of the main references in our work is (Slim et al. 2021a) which provide a design support approach for designing systems by integrating Lean functionalities, with the aim to improve system performance.

Based on our literature review, we identify the gaps related to the integration of Lean requirements during the design phase. The analysis reveal a significant lack of comprehensive lists of Lean requirements and parameters that could serve as industry guidelines. A confusion is found the work of (Slim et al. 2021a) related to the difference of definitions between requirements and functionalities. For this reason, it is essential to clarify this difference and how to take them into account from the early design phases.

Requirements should be seen more as high-level specification. They represent the essential capabilities a system must possess to solve a specific problem or meet a need. They are the “what”, the objectives that the system must achieve. Requirements are problem-oriented and they are usually expressed as explicit statements of what the system must do (criteria, objectives, constraints, performance measures, etc.). They form the basis of the design and provide guidelines on what the system must achieve, but not necessarily how it will achieve it, and form the basis of the functionality definition. Functionalities represent the specific actions or features that a system performs to meet established requirements, the purpose it serves, based on the requirements. In essence, functionalities translate the high-level objectives (from the requirements) into actionable, system-level purposes. They translate requirements into elements that can be used within the manufacturing system (Gdoura et al. 2025).

To effectively design a Leanless system, it is essential to prioritize the identification of requirements adapted to specific problems. By first identifying the issues and challenges, a problem-centered approach is established. This guides the design process toward achieving concrete improvements in identified areas of performance and by consequence the areas of non-performance. In addition, focusing on requirements ensures that the system directly addresses the root causes of problems, and reduces the risk of integrating functionalities that may not be relevant to the core problems, and prevents the deployment of generic Lean tools that may not effectively address the specific challenges encountered (Gdoura et al. 2025).

The main focus of our thesis is based on the lack of work addressing the proactive integration of Lean requirements in the design of manufacturing systems, as well as the lack of guidelines, methodologies, and practical applications to explain how this integration can be achieved. The aim is to design systems with the desired performance from the beginning, minimizing the need for later Lean interventions to correct performance issues.

- *Second Gap: Ambiguous understanding of Lean requirements and a lack of guidelines for integrating Lean requirements and parameters during the design phase.*

2. Industry 5.0 for Advancing Manufacturing Systems Performance

The transition from I4.0 to I5.0 marks a significant shift in industrial practices, moving beyond digital technologies and automation to emphasize sustainability, resilience, and human-centricity. In the following sections, we first examine this transition, outlining the key advancements that define I5.0. We then analyze the literature on the integration of I5.0 principles into systems design. This analysis aims to provide insights into enhancing overall system performance through the adoption of I5.0 concept.

2.1 From Industry 4.0 Towards Industry 5.0

The term Industry 4.0 (I4.0) or the industry of the future was officially presented to the public for the first time by Kagermann, Lukas and Wahlster at the Hanover Fair 2011. The goal of I4.0 is to enable autonomous, intelligent and communicative systems. Technologically speaking, there are 3 main conceptual approaches that define I4.0: Cyber-physical systems, Internet technology and Smart factory. Smart factories are central to I4.0, where “smartness” is realized through the integration of electronic hardware, software, and networking of production resources. Unlike traditional manufacturing systems, smart factories incorporate additional ancillary hardware and software, such as RFID tags, barcodes, laser markers, sensors, and communication networks. These technologies enable machines to collaborate and interact using intelligent analytics, enhancing the overall efficiency and flexibility of the production process (Yang et al. 2018).

I4.0 has been becoming one of the most challenging topic areas in industrial manufacturing engineering within the last decade. All manufacturing systems engaged in the efficient and flexible manufacture of goods must be capable of carrying out all required machining operations with the requisite level of quality. Manufacturing systems must be able to interact and communicate with humans and machines in a dispersed environment, monitor the wear state of functionally important components, and self-adapt their behavior to a particular circumstance to reach to the main objective (Uhlmann et al. 2017). I4.0 technologies help companies achieve more robust, closer, and flexible manufacturing linkages, allowing them to optimize value chains, save costs, and save energy. As well, I4.0 can help manufacturing companies gain flexibility and cost-efficiency in their production processes (Ding et al. 2021).

According to (Laudante 2017), the key technologies and concepts associated with I4.0 include the Internet of Things (IoT), Big Data, Cloud Computing, simulation, Augmented Reality (AR), Robotics, Additive Manufacturing (AM), cybersecurity, and the integration of both horizontal and vertical systems (Figure 8).

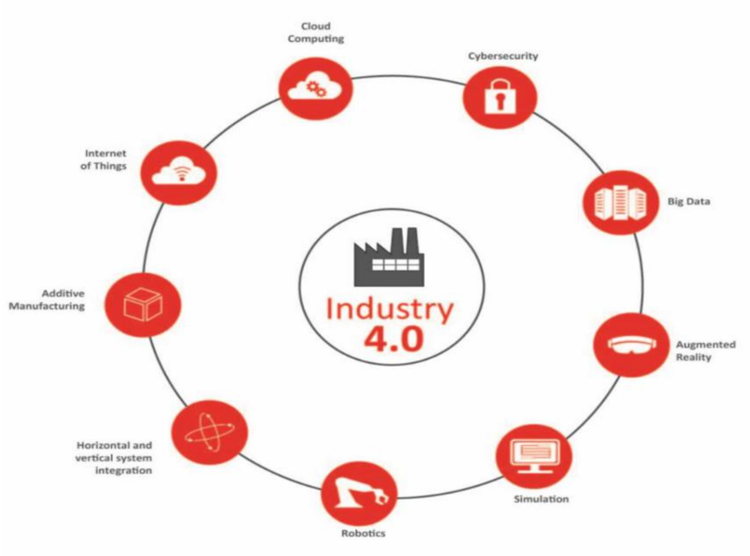

Figure 8: Key Technologies of Industry 4.0 (Laudante 2017)

In January 2021, the European Commission (EC) formally articulated the concept of Industry 5.0 (I5.0), introducing a systematic framework that integrates technological advancements and methodological enhancements. This definition aims to foster a cohesive relationship between key technological drivers and societal development within the context of I5.0. The report of the European Community suggested that I5.0 should be viewed as a progressive extension of the current I4.0 model, rather than a replacement. The proposed framework identifies six crucial categories for I5.0, including Artificial Intelligence (AI), Big Data Analytics, digital twins and simulation, human-machine interaction, bio-inspired technologies and smart materials, and energy efficiency with renewable energy solutions (Rahardjo and Wang 2022). This comprehensive categorization reflects the multifaceted nature of I5.0, aligning technological progress with broader societal and environmental considerations.

Figure 9 provides a concise overview of the evolution of Industrial X.0, highlighting key milestones and advancements that have shaped its development over time.

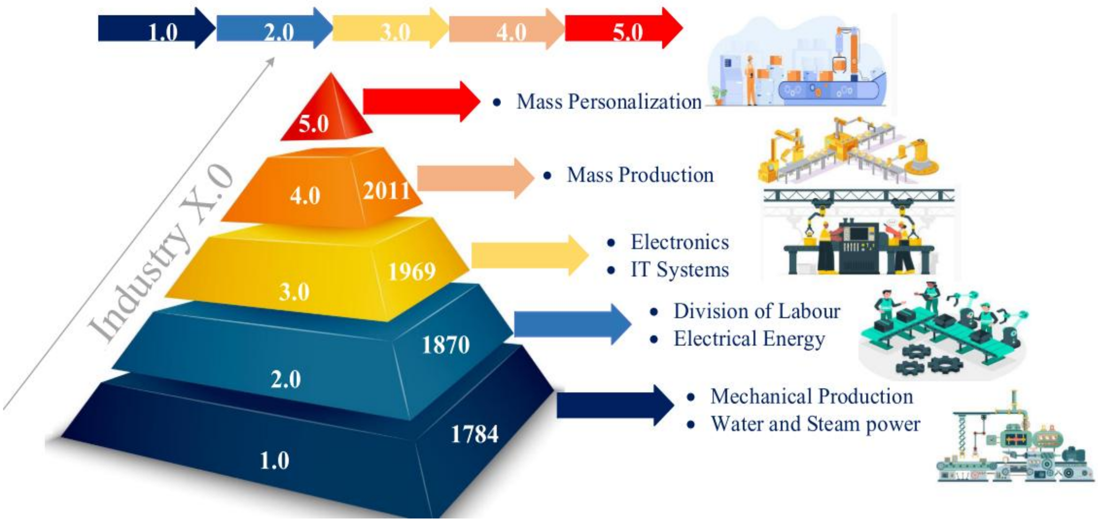

Figure 9: Illustration of Industrial Evolution (Maddikunta et al. 2022)

The EC highlights three critical areas that are anticipated to significantly influence future research and development in manufacturing: (1) Sustainability: emphasizing the reduction of energy consumption, cutting CO2 emissions, minimizing waste, and adopting circular waste treatment practices; (2) Human-Centric Approach: focusing on the enhancement of human skills and both tacit and explicit knowledge, with systems designed to support and augment these capabilities rather than fully replacing them through automation; and (3) Resilience: fortifying processes, factories, and supply chains to improve their robustness and adaptability (Turner and Oyekan 2023).

I5.0 repositions humans at the center of industrial production, supported by tools like Collaborative Robots (Cobots). This approach not only meets current consumer demands for desired products but also provides workers with more meaningful jobs, moving beyond the conventional factory roles that have persisted for over a century. According to (Kovari 2025), the requirements of I5.0 include:

- *Personalization and customization* to meet the needs and preferences of consumers.
- *Flexible manufacturing systems and agile supply chains* to adapt to changing demands.
- *Advanced data analytics and artificial intelligence technologies* to enhance decision-making and operations.
- *Collaboration between humans and machines*, fostering synergy in the workplace and enabling robots to perform repetitive or hazardous tasks.
- *Environmental sustainability*, with efforts to minimize waste, emissions, and resource usage.
- *Circular economic practices*, promoting reuse and recycling of resources to reduce the environmental footprint.
- *Adaptive systems* capable of recovering from shocks and disruptions.

- *Data analytics-driven enhanced decision-making* for predictive maintenance, supply and demand forecasting, and process control.
- *Social responsibility*, upholding ethical standards, protecting workers, and operating in a way that benefits all stakeholders.

To meet these requirements, industries must adopt technologies that enable flexibility, foster collaboration, and promote sustainability. The technologies and principles of I5.0 are: Big data, Cobots, Smart sensors IoT, Internet of Everything (IoE), AI, Multi-agent systems, Digital ecosystem, Smart manufacturing, complex adaptive system, smart materials, 3D printing, 4D printing, 5D printing, 3D scanning, Holography and VR (Rahardjo and Wang 2022), ergonomics, mutual-cognitive Human-Robot Collaboration, recommender system technology, bionics, advanced simulation, Cyber-Physical Systems (CPS), Digital Twin, Metaverse, Extended Reality (XR), blockchain, decentralized computing, cognitive computing, green computing, waste prevention, Smart Materials, disaster mitigation, renewable energy sources, sustainable agricultural production, zero-defect Manufacturing, and fin-tech (Leng et al. 2022).

According to (Ivanov 2023), I5.0 operates across three levels: the societal level, network level, and plant level. It covers four key areas: organization, management, technology and performance assessment. Figure 10 demonstrates the integration of these concepts within the I5.0 framework.

Industry 5.0

	Resilience	Sustainability	Human-Centricity
Society Level	*Viability of intertwined supply networks*	*Sustainable usage of resources and energy on the earth*	*Viability of human-centric ecosystems*
Network Level	*Supply chain resilience* *Reconfigurable supply chain*	*Supply chain sustainability* *Life cycle assessment of value-adding chains*	*Cyber-physical supply chains* *Digital supply chains*
Plant Level	*Resilience of manufactur-ing and logistics facilities* *Reconfigurable plants*	*Reduction of CO2 emissions* *Energy-efficient manufacturing and logistics*	*Human-machine collaboration* *Health protection standards and layouts*

Organisation:
Resilient Value Creation and Usage - Human's Well-being – Sustainable Manufacturing and Society

Management:
Viability as Integrative Perspective of Resilience, Sustainability and Human-Centricity

Technology:
Collaboration – Coordination – Communication – Automation – Identification – Data Analytics

Performance:
Efficiency – Productivity – Resilience – Viability

Figure 10: Industry 5.0 Framework (Ivanov 2023)

One of the main concepts of I5.0 is Society 5.0, its vision is characterized by four parallel concepts, namely, “a human-centric society”, “merging cyberspace with physical space”, “a knowledge-intensive society” and “a data-driven society”, as shown in Figure 11 (Leng et al. 2022).

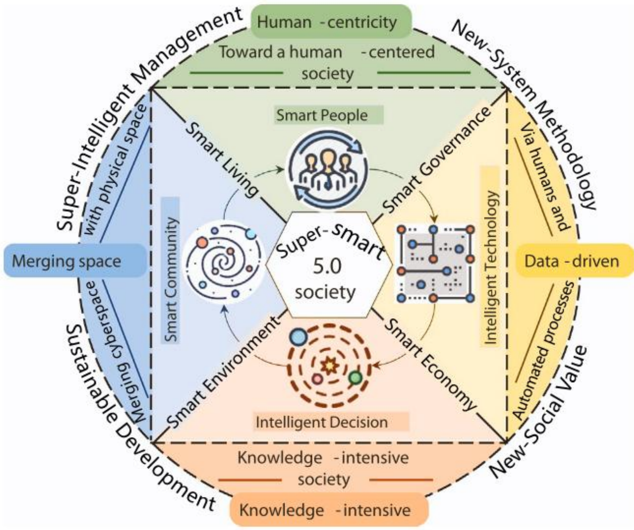

Figure 11: Concept of Society 5.0 (Leng et al. 2022)

During I4.0, efforts were made to control human activity by prioritizing the automation of processes, often placing humans in competition with machines and removing them from many scenarios. In contrast, I5.0 aims to strike a balance, fostering human-machine collaboration that maximizes benefits such as cost optimization through efficient processes, environmentally friendly solutions, and creative customization to meet customer demands.

According to the EC report and recent studies, I5.0 differs from I4.0 in five key aspects (Espina-Romero et al. 2023):

1. I5.0 emphasizes competitiveness driven by productivity alongside sustainable development;
2. It empowers the workforce by prioritizing people-centered strategies for technological progress. The concept of Operator 4.0 has recently evolved into Operator 5.0, which focuses on improving the resilience of manufacturing systems by empowering humans to collaborate with automation solutions. Operator 5.0 should work alongside equipment, utilizing their own physical, sensory, and cognitive abilities in an environment that ensures safe working conditions and technological support in tasks where human involvement is essential. Meanwhile, technologies will offer real-time information to facilitate timely decision-making (Zizic et al. 2022);
3. It depends on the use of effective technologies and standards to expand the application of industrial responsibility across the entire value chain;
4. It emphasizes the crucial role of stakeholders in driving innovation, managing technology, and enhancing sustainability performance;
5. It fosters technological innovation focused on environmental sustainability.

I4.0 focuses on smart production driven by technologies like cloud computing, IoT, Big Data, and AI, with the primary motivation being mass production. Its energy supply includes electricity and fossil-based fuels, emphasizing technological advancements for process improvement and innovation within business administration. In contrast, I5.0 shifts towards a human-centric approach and sustainability, evolving into two main concepts: Human-robot symbiosis and a bioeconomy focus. Renewable energy becomes more prominent, while technologies pivot towards human-robot collaboration and sustainable production methods. The involved areas expand to include smart environments and waste management, reflecting I5.0's broader emphasis on ecological and societal well-being alongside economic progress (Thomaz and Bispo 2022). During I4.0, the focus was on automating processes, often positioning humans in competition with machines and leading to the displacement of people in many areas. However, with I5.0, the aim is to strike a balance where human-machine collaboration yields optimal results, fostering cost savings through efficient processes, environmentally sustainable solutions, and the creative customization that customers increasingly demand (Espina-Romero et al. 2023).

I4.0 has limitations in advancing industrial sustainability and safeguarding workers' well-being, as it primarily focuses on improving production efficiency and flexibility through digitalization and technology. As a result, I4.0 has become more technology-driven than human-centered, often overlooking the importance of the human factor in productive systems (Alves et al. 2023). Table 1 presents a comparison of the primary objectives and approaches between I4.0 and I5.0.

Table 1: Key differences between Industry 4.0 and Industry 5.0 (Agote-Garrido et al. 2023)

	Industry 4.0	Industry 5.0
Objectives	Intelligent and interconnected production process. System optimization.	Social benefit. Human-centric. Sustainability. Environmental care. Sustainability. Resource management.
Human Factor	Human–machine interaction. Human reliability.	Ethical use of technology to promote human values and needs. Worker management and safety.
Environment	Higher material consumption. Higher energy consumption.	Awareness and waste recycling. Renewable energy sources.
Resilience	Automatic fault detection. Autonomous decision-making.	Human adaptation to unexpected situations. Interoperability.

According to (Golovianko et al. 2022), two distinct approaches exists to navigating the landscapes of I4.0 and I5.0 concurrently. The first approach involves their co-existence, where both paradigms operate somewhat independently. Under this co-existence model, the evolution of the concept of Cyber-Physical Systems within I4.0 is observed transitioning into Cyber-Physical-Social Systems in the I5.0 context. The success of this co-existence hinges on the augmentation of productivity without the exclusion of human workers from manufacturing processes. Alternatively, the second approach advocates for a more transformative stance, wherein I4.0 undergoes a deliberate shift towards I5.0. This transition is envisioned as a comprehensive process addressing key social expectations and focusing on three pivotal developmental areas: human-centric, sustainable, and resilient. The transformation process prioritizes principles of sustainable development and seeks to enhance the overall quality of life.

With the belief that I4.0 and I5.0 should neither replace one another nor exist in isolation, a hybrid perspective takes shape, envisioning their integration. In this scenario, humans are reintegrated into I4.0 processes, aligning with the human-centric principles of I5.0, while I4.0 technologies are adapted to address environmental sustainability and resilience demands.

The implementation of new technologies can lead to negative environmental effects, such as air pollution and increased consumption of raw materials and energy. However, even using these technologies, energy consumption can be minimized through data analysis during manufacturing and across the supply chain. Furthermore, the technology selection process should integrate environmental and social criteria, prioritizing greener and more sustainable options, even if they may offer lower productivity (Zizic et al. 2022). This innovative approach envisions a harmonious fusion where the strengths of both I4.0 and I5.0 are harnessed synergistically, offering a pathway that combines efficiency, sustainability, and the reintroduction of human influence through cutting-edge digital intermediaries.

2.2 Integration of Industry 5.0 Principles into Systems Design

With the emergence of I5.0, technologies must now support human roles within the manufacturing system, promoting human-centric design, while also respecting environmental considerations. Therefore, the technologies integrated into the design must be considered with these I5.0 principles from the beginning.

Some studies have attempted to integrate the principles of I5.0 into systems design, recognizing the growing importance of aligning production processes with the evolving needs of modern industries. I5.0 emphasizes a more human-centric, sustainable, and resilient approach to manufacturing, focusing on the synergy between advanced technologies and human capabilities. As a result, researchers and practitioners have explored various ways to incorporate these principles into system design, aiming to enhance operational efficiency, adaptability, and environmental sustainability. However, challenges remain in fully integrating these concepts, particularly in balancing technological advancements with human well-being and long-term sustainability goals.

In the following, we present some of these works that tried to integrate I5.0 from the design phase. (Orso et al. 2022) emphasize the importance of involving employees directly from the earliest stages of design projects to align with the Human-centric principle of I5.0. They utilize a mixed-method approach, combining employees' self-reported data with objective, event-based data derived from in-the-field video analysis. (Mourtzis et al. 2022) propose a novel conceptual design of automatic tool changer for collaborative robots under the framework of I5.0 to ensure that the device does not break down during operation and endanger human life. (Kaasinen et al. 2022) examine the design of resilient human-machine teams and their collaborations to explore the opportunities and challenges in creating seamless human-machine teams for I5.0 manufacturing systems. (Klein and Gutowska 2022) analyze the incorporation of restorative design principles into I5.0 and its role to promotes a sense of wellbeing and to help in the areas of sustainable systems, natural resources and human health. (Ivanov 2023) discuss the opportunities arising from combining organizational principles and technologies aligned with I5.0 to transform existing business model designs and to create and manage operations and supply chains with I5.0 principles in mind. (Peruzzini et al. 2023) propose a Smart Manufacturing Systems Design framework that facilitates I5.0, focusing on the symbiosis between humans and automation. (Agote-Garrido et al. 2023) propose a theoretical model for manufacturing system design that utilizes sociotechnical systems to integrate I4.0 enabling technologies, while also considering the key aspects of I5.0.

The mentioned works, along with others addressing the integration of I5.0 principles into system design, focus primarily on individual principles, lacking a methodology that encompasses the integration of all three fundamental principles of I5.0 in a single approach.

- *Third Gap: Studies aiming to integrate I5.0 from the design phase, although limited in number, tend to address its principles separately, with limited existing research focusing on the integration of all three main principles of I5.0.*

3. Combining Lean and Industry 4.0

To analyze the evolution of the Lean paradigm in a temporal sequence, this section examines the complementarity between Lean and I4.0, as well as studies that aim to combine and integrate Lean and I4.0 technologies into system design. This analysis allows us to identify the limitations that lead to the introduction of the Lean 5.0 paradigm and the integration of its requirements from the design phase.

3.1 Industry 4.0 as a Framework to Lean Applications

The fundamental feature and objective of Lean production systems is the creation and execution of efficient Lean processes with exact standards and a strong customer orientation. In the same frame, I4.0 provides for a strong integration of consumers and suppliers in the process by implementing a horizontal and vertical network (Dombrowski et al. 2017). The authors have found different interdependencies, which have been grouped into four categories: Lean serves as a foundation for I4.0; I4.0 complements Lean; I4.0 improves Lean's efficiency; and I4.0 modifies Lean's concepts.

The term “Lean” consists of variety of production processes, including product creation, procurement, manufacturing, and distribution. It is adopted as a mentality as well as a collection of tools and processes in order to attain the greatest quality, lowest cost, and quickest Lead time possible. In the same frame, I4.0 might be viewed as a future strategy for remaining competitive. It focuses on value chain optimization as a result of dynamically and autonomously managed manufacturing. In addition, it entails the creation and implementation of competitive products and services, as well as the development and implementation of robust and adaptable administrative, logistical, and production systems (Mrugalska and Wyrwicka 2017).

(Kolberg and Zühlke 2015) demonstrate the combination of Lean and I4.0 technologies, aiming to integrate information and communication technologies (ICT) to enhance Lean Production. Some of those combinations are:

- Smart Operator

The Smart Operator can reduce the time between failure incidents and failure notifications by using the Andon method, which ensures that employees are alerted as quickly as possible when a failure occurs. Smartwatches can be used to send real-time error notifications and indicate the location of the issue. Additionally, employee assistance systems based on augmented reality (AR) can help maintain a continuous flow of parts by providing real-time, visual information about cycle times. This AR-enabled system ensures just-in-time delivery of items, improving efficiency and minimizing delays.

- Smart Product

Based on Kaizen, during and after manufacture, Smart Products might gather process data for analysis; in addition, the Kanban information in a Smart Product might be used to regulate manufacturing operations.

- Smart Machine

The Smart Machine is reconfigurable, flexible, and capable of operating autonomously through RFID technology. It can also notify the operator in real time in case of a failure (Poka-yoke) to prevent errors. Additionally, by utilizing Plug'n Produce technology, changeover times (set-up times) can be reduced to less than 10 minutes, enhancing flexibility and minimizing unplanned stops, thus improving overall operational efficiency (Mrugalska and Wyrwicka 2017).

- Smart Planner

Traditional Kanban systems, with fixed numbers of Kanbans, cycle periods, and round trips for delivering items, evolve into dynamic production systems that automatically adapt to current production schedules through the use of the Smart Planner. This shift allows for more flexibility and responsiveness, optimizing the flow of materials and ensuring that production aligns with real-time demands.

Lean 4.0 is a recent specifier of Lean concept. It was introduced in 2017 by (Metternich et al. 2017). Lean philosophy was considered a requirement for digitalization, according to the authors' analysis of the relationship between Lean and the technologies covered by I4.0. With the advent of Lean 4.0, the integration process has evolved by incorporating digital technologies, enabling the digitalization of Lean tools and the use of advanced technologies such as Big Data Analytics, Automated Guided Vehicles (AGVs), virtual simulations, sensors, robots, etc.

Various studies have explored the relationship between Lean tools and I4.0 technologies. For example, (Mayr et al. 2018) present a matrix illustrating how I4.0 tools can support Lean methods. (Valamede and Akkari 2020) propose different combinations of I4.0 technologies and Lean tools, while (Valamede and Akkari 2021) present a relationship matrix between Lean manufacturing wastes and digital technologies.

Building on this understanding of Lean 4.0, the next section explores how its principles can be integrated into the design phase of manufacturing systems.

3.2 Lean 4.0 to Improve Manufacturing Systems Design

Traditional Lean integration primarily focuses on applying Lean tools to enhance the performance of existing systems. The shift from traditional Lean to Lean 4.0 represents a significant change in how Lean principles are integrated with advanced technologies on existing systems. Despite the importance of this integration, few studies have explored it from the manufacturing system design phase.

The integration of Lean 4.0 from the design phase has gained attention from some researchers; however, their focus has primarily been on product design rather than manufacturing system design. For example, (Dahmani et al. 2021) propose a framework that combines Lean design, eco-design, and I4.0, incorporating the circular economy paradigm into product development. Their approach aims to design eco-efficient products, providing guidance for designers and manufacturing managers to develop products that align with customer needs while meeting sustainability requirements. The primary goal is to ensure the development of products that minimize negative environmental impacts.

Some other researchers have focused on integrating Lean 4.0 into the design process. For example, (Dillinger et al. 2021) propose a concept that serves as a guideline for developing a Lean 4.0 reference implementation strategy for manufacturing companies. This theoretical framework outlines tasks for designers and experts to assess the current status and identify how to select Lean and I4.0 elements, without prescribing the specific tools and principles to be integrated or detailing the methods of their incorporation into manufacturing systems. (Schumacher et al. 2022) develop the Lean 4.0 toolbox to design and optimize corporate processes. The Lean 4.0 toolbox offers systematic support for managing complexity in industrial engineering. It provides advantages in operational knowledge management, promotes employee participation, and facilitates the implementation of the learning organization principle.

Few researchers have explored the integration of Lean 4.0 in the design of manufacturing systems. (Schumacher et al. 2023) present a systematic literature review of the rapidly evolving field of Lean Production Systems 4.0, with a particular focus on their design by industrial engineers. The authors describe the essential qualitative requirements and guidelines for the design of Lean Production 4.0 systems. The listed requirements focus on the systematic management, standardization, and digital integration of methods and tools to enhance efficiency and scalability in industrial engineering and production systems. They emphasize documentation, simplification, modular design, and the structured rollout of digital solutions, ensuring adaptability to different Lean and I4.0 maturity levels. The proposed guidelines primarily address the adaptation of existing production systems to improve efficiency, responsiveness, and digital integration.

Complementary to the second gap regarding the lack of guidelines for integrating Lean requirements into the design of manufacturing systems, there is also a noticeable gap in guidelines that define the different combinations of Lean and I4.0 and their integration from the design phase of manufacturing systems.

Few studies have explored Lean 4.0 in the context of design, and the theoretical frameworks proposed remain unvalidated by practical results. It can be concluded that there is a notable lack of research directly addressing Lean 4.0 from the design phase of manufacturing systems. Furthermore, empirical studies on this topic are limited.

- *Fourth Gap: Lack of empirical studies evaluating the integration of Lean 4.0 tools from the design phase of manufacturing systems.*

This fourth gap was initially identified at the beginning of our PhD and has been discussed in our article, which represents the starting point of our research (Gdoura et al. 2024a). In this article, we conducted an empirical study, through a questionnaire survey, to evaluate the impact of integrating Lean 4.0 tools from the design phase. However, based on the results we obtained and further investigations into the limitations of Lean 4.0, we have addressed these shortcomings by exploring the combination and the integration of Lean and I5.0 concepts. This transition aims to overcome the limitations of Lean 4.0 and enhance the integration of Lean requirements within the context of I5.0, particularly focusing on the fundamental principles of I5.0: Sustainability, resilience, and human-centricity.

The limitations of Lean 4.0 are especially apparent in its insufficient focus on human and social factors within organizations, including aspects like leadership, employee integration, and the training required for new roles and responsibilities. Additionally, Lean 4.0 frameworks often overlook critical aspects of sustainability, including social, financial, and environmental concerns. Lean 4.0 tends to focus primarily on technology integration and operational efficiency, with minimal consideration for long-term business sustainability or resilience. Specifically, environmental sustainability is frequently identified as a gap in Lean 4.0 literature, and the social dimension is often neglected, limiting the Lean 4.0's ability to address the full scope of modern industrial challenges (Moraes el al. 2023).

With the emergence of I5.0, additional constraints have arisen. Technologies must now support human roles within the manufacturing system, promoting human-centric design, while also respecting environmental considerations. Therefore, the technologies integrated into the design must be considered with these I5.0 principles from the beginning.

The following section analyzes the synergies between Lean and I5.0, highlighting how their integration can enhance manufacturing system design.

4. Combining Lean and Industry 5.0 Principles

Starting with classic Lean and progressing through Lean 4.0, the emergence of I5.0 and the few attempts to clarify the synergy between Lean and I5.0 concept present a significant opportunity to introduce a new paradigm shift "Lean 5.0". Lean 5.0 integrates the traditional efficiency-driven principles of Lean with the human-centric, sustainable, resilient, and technologically advanced vision of I5.0. While Lean focuses on waste reduction and value creation, Lean 5.0 expands these principles by incorporating advanced technologies and aligning them with the core principles of I5.0. In the following sections, we explore the various relationships between Lean and I5.0 concepts, analyzing their integration into system design and the rationale behind our proposal for the Lean 5.0 concept.

4.1 Relationship between Lean and Industry 5.0

In our research, we emphasize the importance of defining Lean requirements that directly address identified issues in the manufacturing process while encompassing multiple performance criteria and domains. Our focus goes beyond simply integrating Lean requirements; it extends to aligning them with the I5.0 principles. This preparatory step is important to ensure that the system is designed from the beginning with both Lean and I5.0 principles in mind. By incorporating sustainability, resilience, and the role of humans as key factors during the requirements specification phase of the production system design, we can ensure that automation and advanced technologies, when integrated in subsequent design stages, are already aligned with these essential considerations. Another key advantage of our proposal is that, when modifying existing systems, employees often struggle to adapt to new tools and practices, preferring traditional work habits. By integrating Lean requirements and I5.0 considerations from the design phase of future systems, employees will be more adaptable, as they will find that both principles have been considered from the beginning.

The synergy analysis of Lean and I5.0 principles is receiving increasing attention, mainly in adapting the existing systems. Few studies have focused on this synergy, exploring how these two approaches can complement each other to drive innovation and efficiency in manufacturing. (Mladineo et al. 2021) analyze the importance of human elements in the successful implementation of Lean principles in SMEs in an I5.0 context. (De souza et al. 2022) conduct a systematic literature review of the concepts of the Lean approach, I4.0, and I5.0, providing insights into their interconnections. (Moraes et al. 2023) examine the relationship between Lean and I4.0, exploring the potential for integration with the new concept of I5.0. They assess how Lean principles can align with the core elements of I5.0 through cause-and-effect relationships. They highlight that the “Human-Centric” perspective of I5.0 is closely aligned with Lean principles.

(Eriksson et al. 2024) investigate how Lean production practices and I4.0 technologies can coexist to improve manufacturing operations in the era of I5.0, based on a longitudinal case study. The authors identify the challenges that manufacturing organizations face, emphasizing the need to move beyond Lean and I4.0 philosophies to address the demand for a human-centered approach to socially sustainable manufacturing in the context of I5.0. (Fani et al. 2024) explore the synergies between Lean, I4.0, and I5.0 principles, aiming to demonstrate how Lean’s focus on people enhances the implementation of I5.0. They propose a framework to understand how Lean integrates into the Human-Centric paradigm of I5.0. (Boumsisse et al. 2025) emphasize the significance and potential of integrating I5.0 technologies into the Green Lean Six Sigma DMAIC cycle to enhance the sustainability and efficiency of production processes.

Based on our literature review, previous works have explored the relationship between Lean and I5.0 as broad concepts, focusing on the coexistence of Lean production practices and I4.0 technologies in the transition to I5.0. In our research, we expand on this global interaction by examining the relationship between each Lean tool/method and the core principles of I5.0. While some studies have investigated the connection between specific Lean tools/methods and individual I5.0 principles, we observe a gap in the literature, with the lack of comprehensive work that analyzes and summarizes the relationship between Lean tools and the three principles of I5.0.

- *Fifth Gap: Lack of analysis on the relationship between Lean tools and the fundamental principles of I5.0.*

Given the lack of studies analyzing the synergy between Lean and I5.0 principles, we took a step back to examine how Lean have already addressed sustainability, resilience, and human-centricity, key aspects of I5.0, even before the concept emerged. This analysis allows us to understand how Lean inherently incorporates these principles, independent of the technological advancements emphasized in I5.0.

4.2 Analysis of the Convergence between Lean and Industry 5.0 Principles

As previously mentioned, despite the significance of Lean 4.0, it has several limitations that our work aims to address. We initiate the transition toward Lean 5.0 by analyzing the synergy between previous Lean paradigms and I5.0 principles, even before the official announcement of I5.0. Various Lean concepts highlight this synergy, such as Sustainable Lean (Maqbool et al. 2019), which promotes eco-friendly practices within Lean frameworks; Lean Green (Verrier et al. 2016), which focuses on reducing waste and environmental impact; Human-Centered Lean (Hines 2022), which emphasizes the importance of human involvement and empowerment in Lean processes; Lean Safety (Hafey 2017), which integrates safety into Lean practices to ensure both efficiency and well-being; and Lean Resilience (Ivanov 2022), which focuses on creating robust systems that can adapt to changes and disruptions. Together, these concepts among others highlight how Lean principles can support the goals of I5.0, fostering a more sustainable, resilient, and human-focused approach to technological progress.

In this section, we conduct a literature review to analyze the relation between I5.0 principles (Sustainability, human-centricity and resilience) and 12 of the most common Lean tools cited in the literature. The application of Lean tools are not always one-size-fits-all solutions for all I5.0 principles; their effectiveness depends on their ability to address the unique challenges and goals associated with each principle. However, sometimes the application of such Lean tools for enhancing one principle of I5.0 can directly have a positive impact of other principles. By gearing the integration of Lean tools to the specific requirements of each objective, companies can leverage the most appropriate and effective technologies and practices. This focused approach ensures that Lean tools are not only implemented correctly, but also have maximum impact, achieving optimal results to the company. In addition, this precise focus prevents misalignment of resources and efforts, ensuring that every aspect of the Lean integration process is strategically focused on achieving the designated objectives.

Considering the 23 selected publications listed in Table 2, we analyze the convergence between the selected Lean tools and the principles of I5.0. The inclusion criteria required that each publication focus on smart, green, resilient, and Lean (SGRL) manufacturing systems, be published between 2015 and 2024, offer relevant insights for SMEs, and be accessible through academic databases such as Scopus, Web of Science, or IEEE Xplore. These works are categorized into two groups: Studies that explored the synergy between Lean and I5.0 principles prior to the official recognition of I5.0, and studies that integrate I4.0 technologies to enhance Lean tools in addressing sustainability, resilience, and human-centricity. However, these studies do not establish a direct link between Lean and the I5.0 concept.

Table 2: Convergences between Lean Tools and Industry 5.0 Principles

References	I5.0 Principles			Lean Tools											
	Sustainability	Human-centricity	Resilience	JIT	SMED	5S	Kanban	Poka-Yoke	VSM	TPM	Heijunka	Andon	Kaizen	Jidoca	Standardisation
(Ng et al. 2015)	X				X	X	X				X				
(León and Calvo-Amodio 2017)	X			X	X	X	X	X	X	X		X	X		
(Maqbool et al. 2019)	X				X				X	X			X		
(Romeira et al. 2020)	X			X			X								
(Kumar and Mathiyazhagan 2020)	X				X	X	X	X	X	X			X		X
(Kabzhassarova et al. 2021)	X			X		X	X	X	X				X		
(García-Alcaraz et al. 2021)	X				X	X									
(García-Alcaraz et al. 2022)	X							X		X		X	X	X	
(Ciannella and Santos 2022)	X					X									
(Khakpour et al. 2024)	X				X										
(García-Cutrín and Rodríguez-García 2024)	X			X											
(Stadnicka and Antonelli 2019)		X		X	X	X	X	X		X	X	X	X		X
(Wang et al. 2022)		X							X						
(Fonda and Meneghetti 2022)		X			X	X									
(Wan and Leirmo 2023)		X						X		X					
(Powell 2024)		X										X		X	
(Habibi Rad et al. 2021)			X	X						X					
(Reke et al. 2022)			X	X				X		X	X		X	X	X
(Abdullah et al. 2023)			X		X	X	X		X		X		X		X
(Potthoff and Gunnemann 2023)			X			X	X		X			X			X
(Choi et al. 2023)			X	X											
(Bajic et al. 2023)			X										X		
(Wolniak 2024)			X					X							

To bridge the gap between Lean and I5.0, it is essential to analyze how Lean principles align with the three core pillars of I5.0, in addition to the technological advancements of I4.0. While I4.0 primarily focuses on digital transformation, automation, and smart technologies to enhance efficiency, I5.0 extends beyond this by emphasizing sustainable development, system adaptability, and the central role of human workers. The following sections detail the complementarity between Lean and key I5.0 principles, as presented in Table 2.

4.2.1 Sustainability

In order to evaluate how Lean tools contribute to the sustainability principle, we carry out a literature review. (Ng et al. 2015) propose a methodology aimed at integrating Lean and Green practices, along with metrics derived from their implementation. They assess the application of various Lean tools to reduce waste streams, leading to improvements in sustainability and Green performance. (León and Calvo-Amodio 2017) identify and analyze the interconnections between Lean practices and sustainability, examining their impact on performance from operational, financial, societal, and environmental perspectives. (Maqbool et al. 2019) identify the gap of the integration of Lean practices with 6Rs (reduce, reuse, recycle, recover, redesign and remanufacture) and develops a framework which implemented on the case study that carries ability to attain 6R based sustainable Lean production systems. Three main Lean tools that support sustainability through the 6Rs were presented: VSM, SMED and TPM. (Romeira et al. 2020) present a comparative study of the environmental impacts of the Kanban system, evaluating Green Key Performance Indicators (KPIs) such as energy usage, material usage, water usage, waste, and air and water pollution. This analysis provides a comprehensive view of Kanban's environmental impacts, allowing for proactive measures to prevent them. (Kumar and Mathiyazhagan 2020) explore the integration of Lean practices with sustainable manufacturing and analyze the effects of their implementation in the manufacturing industries. (Kabzhassarova et al. 2021) conduct a systematic literature review on the separate and combined effects of Lean and I4.0 on the three pillars of sustainability (economic, environmental, and social). They present various sustainability indicators to evaluate the impact of Lean and I4.0 concepts. (García-Alcaraz et al. 2021) present a second-order Structural Equation Model (SEM) that analyzes three Lean manufacturing tools related to material flow (5S, SMED) and continuous flow, focused on economic sustainability. In a subsequent study (García-Alcaraz et al. 2022), the authors introduce and validate a SEM that links eight Lean manufacturing tools, integrated into three independent latent variables: continuous improvement (Kaizen and Gemba), supporting tools (Andon, visual management, and Poka-yoke), and machinery and equipment (TPM, overall equipment effectiveness, and Jidoka). These are correlated with social, economic, and environmental sustainability as dependent variables.

(Ciannella and Santos 2022) conduct an exploratory study using the analytic hierarchy process (AHP) to connect Employee Social Sustainability (ESS) with Lean practices, based on expert opinions. Their findings highlight that 5S is considered the most influential Lean practice on ESS. (Khakpour et al. 2024) recommend SMED 4.0 to avoid defect occurrence during production and improve triple bottom line sustainability in manufacturing processes, besides reducing setup time. (García-Cutrín and Rodríguez-García 2024) employ a meta-analytic approach to explore the correlation between JIT practices and financial performance. Their study aims to refine processes and eliminate inefficiencies, which in turn helps sustain financial gains and competitive advantages, while also supporting environmental and social sustainability objectives.

The previous work has demonstrated the effectiveness of various Lean tools in improving the sustainability objectives of I5.0. The main purpose of using Lean tools to enhance sustainability lies in their ability to minimize and eliminate different types of waste in the using phase of existing manufacturing systems. In addition, these tools facilitate the conversion of waste into usable materials after its post-use cycle, thus contributing to a circular economy.

4.2.2 Human-Centricity

In this section, recent studies that connect Lean tools with human requirements are presented. (Stadnicka and Antonelli 2019) analyze the most common Lean strategies in the context of establishing a collaborative work cell. They propose a methodology for redesigning an industrial assembly cell based on the Human-Robot Collaboration principle. Additionally, they discuss a set of Lean tools in relation to the collaborative workspace level. (Wang et al. 2022) propose an improvement model that combines DMAIC with VSM 4.0 for a truck cooler manufacturer. This model aims to enhance the picking workstation design, incorporating a human-centered approach. (Fonda and Meneghetti 2022) develop Human-Centric SMED (H-SMED) framework to rethink and manage the setup process by integrating I4.0 tools, Lean Management and Ergonomics with a new attention to the centrality of workers, in order to guide the transition towards the next I5.0. It focus on the re-qualification of manpower with new competences in order to deal with the digitalized world. (Wan and Leirmo 2023) contribute to the development of a roadmap for human-centric zero-defect manufacturing, aiming to eliminate defects and enhance the resilience of the manufacturing sector. They analyze the role of Lean manufacturing in empowering employees, with a specific focus on tools such as Poka-Yoke and TPM. (Powell 2024) introduce Jidoka as the fundamental to Lean's respect for people principle and investigates the role of AI in Lean manufacturing to enhance human learning.

Based on the above studies, we note that Lean tools and the human-centricity principle in I5.0 are deeply connected through their shared focus on empowering people and enhancing their role in the workplace.

4.2.3 Resilience

In this section, we present studies that explore the relationship between Lean tools and resilience. (Habibi Rad et al. 2021) provide a systematic literature review that analyzes the integration of Lean and resilience paradigms, examining their application, compatibility, and impact in the context of supply chains. They also explore conceptual development and operational research across various organizational and industrial sectors. (Reke et al. 2022) present preliminary results from two Norwegian manufacturing companies applying Toyota Production System (TPS) concepts to build a resilient and responsive manufacturing system through an action learning process. They also identified a set of Lean tools that reveal learning and development opportunities in the form of problems, leading to a learning process known as "Problem-Based-Learning". (Abdullah et al. 2023) demonstrate how smart, green, resilient, and Lean (SGRL) techniques can help SMEs to obtain optimal performance and to provides different combinations of SGRL practices. (Potthoff and Gunnemann 2023) conduct a systematic literature review to evaluate the resilience of Lean production systems. They investigate whether there is a correlation between the design of a production system based on Lean principles and the resilience of that system. (Choi et al. 2023) present various approaches to adapt JIT for turbulent environments, aiming to build resilience in supply chains and enhance overall performance. (Bajic et al. 2023) examine Digital Kaizen, as I5.0 continuous improvement methodology enabled by advanced technologies to improve the workforce's productivity, rather than simply to replace workers. (Wolniak 2024) analyze the integration of Poka-Yoke with I4.0 as a transformative leap in error prevention methodologies, aligning perfectly with the goals of advanced manufacturing and creating resilient, reliable processes that produce consistent high-quality output.

The conclusion that can be drawn from the preceding work is that Lean tools and the resilience principle are closely aligned, as both aim to create robust and adaptable systems.

Lean concepts such as Lean Green, Lean sustainability, Lean safety and Lean resilience embody I5.0 principles, illustrating how Lean practices can achieve I5.0 objectives. This synergy suggests the possibility of improving manufacturing processes by integrating Lean requirements with I5.0 principles, thus fostering a more sustainable, resilient and people-centered industrial environment.

Numerous studies have explored the synergy between Lean and I5.0 principles, as well as the role of integrating I4.0 technologies to enhance the functionalities of Lean tools in addressing these principles, highlighting their compatibility and complementarity prior to the official announcement of I5.0. However, few studies have identified a direct link between Lean and I5.0 or provided a comprehensive view of how Lean can align with the new requirements introduced by the formal recognition of I5.0. Additionally, limited research has attempted to combine and integrate these two concepts from the design phase of manufacturing systems. This gap underscores the need for a paradigm shift, from the passive coexistence of Lean and I5.0 principles to their proactive integration from the beginning. This perspective sets the stage for the following sections, where we further examine this integrative approach and its impact on manufacturing system performance.

4.3 Integrate Lean and Industry 5.0 to Design Manufacturing Systems

Few studies have tried to integrate the both concepts of Lean and I5.0 in the design of systems. (Rahardjo and Wang 2022) introduce a novel sustainable innovation framework that combines inductive and integrative approaches, leveraging Lean Six Sigma (LSS) tools and I5.0 technologies to achieve process excellence. They present six LSS 5.0 tools and provide implementation guidelines using the DMAIC methodology. Similarly, (Rahardjo et al. 2024) develop the RIDEM (Requirements, Initiation, Design, Execution, and Monitoring) approach for LSS 5.0 implementation. These two studies represent some of the earliest studies addressing the integration of Lean and I5.0 in the design process context. However, their contributions offer a general framework that highlights the significance of combining Lean tools and I5.0 principles, without specifying how this integration should be implemented.

According to our research, there is a notable absence of comprehensive methodologies or guidelines for integrating Lean tools and principles within the context of I5.0 during the design phase of manufacturing systems. While existing studies highlight the importance of combining Lean principles with I5.0 technologies to improve the processes of existing systems, we didn't find clear, actionable strategies for implementing this integration effectively during the early stages of system design. This gap in the literature leaves a critical need for frameworks or approaches that can guide designers in integrate Lean tools in a way that aligns with the principles of I5.0.

- *Sixth Gap: Absence of guidelines and methodologies for formulating and integrating Lean tools added values during the design phase of manufacturing systems in an I5.0 context.*

5. Lean/Industry 5.0 and Design Methods

Our aim to propose a Lean 5.0 model for designing manufacturing systems introduces certain complexities. To address this, we first analyze the various criteria related to both Lean and I5.0 concepts by examining Design for X (DfX) methodologies. To tackle the complexity of modeling a Lean 5.0 system, we introduce the AD method in the second section and review the literature that has attempted to model Lean and I5.0 principles using this method. In the third section, we explore the relationship between Lean and TRIZ to verify the complementarity of these two concepts. In each section, we identify gaps that we will address in the subsequent discussions.

5.1 Lean/Industry 5.0 and Design for X

To meet evolving customer expectations, companies need to take into consideration most challenging requirements. To help designers meet these increased needs, various methodologies, known as "Design for X (DfX)", have been created.

The selection of DfX methodology in our work is justified by its capacity to integrate multiple performance criteria into systems design, enabling us to anticipate and address potential issues effectively. By focusing on various aspects, DfX ensures that the final products and systems align with user requirements and production constraints. Furthermore, its inherent flexibility allows for adaptation to technological advancements and evolving market demands, making it particularly suitable for developing systems within the Lean and I5.0 contexts. Additionally, the selection of DfX is based on the established definitions of the X criteria and the proven effectiveness of their integration into system design.

As sustainability challenges continue to grow, companies are increasingly adopting DfX as a concurrent approach that addresses multiple issues through various factors, or "Xs", to meet customer requirements. DfX is regarded as one of the most effective methods for tackling challenges such as time-to-market, product cost, product quality, and customer satisfaction (Benabdellah et al. 2020). This approach is used to enhance both the product design and the process design, focusing on specific perspectives represented by the "X". The "X" can refer to different stages in the product life cycle or desired criteria and domains, such as maintenance, safety, and cost.

Within each "X" domain lies a set of influential variables that deserve analysis. We evaluate these domains to identify the ones that are most relevant and best aligned with Lean and I5.0 concepts. To identify the most prominent DfX methodologies, we conduct a literature review. In the following, we present the selected criteria and summarizes 34 of the most cited DfX methodologies and its description which shows its importance in our aim to design a Leanless high-performance system. By grounding our study in the analysis and integration of various DfX methodologies, we are able to design systems that excels in multiple performance dimensions, including operational performance, financial performance, environmental performance and social performance.

Many DfX techniques share similar concepts but are referred to by different names, while others use the same terminology but differ in meaning, approaches, and guidelines. Hence, we have classified the 34 DfX methodologies referenced in an hierarchical representation, grouping them based on their interconnections and shared objectives. This classification is illustrated in Figure 12, where the DfX elements within the same box share common objectives.

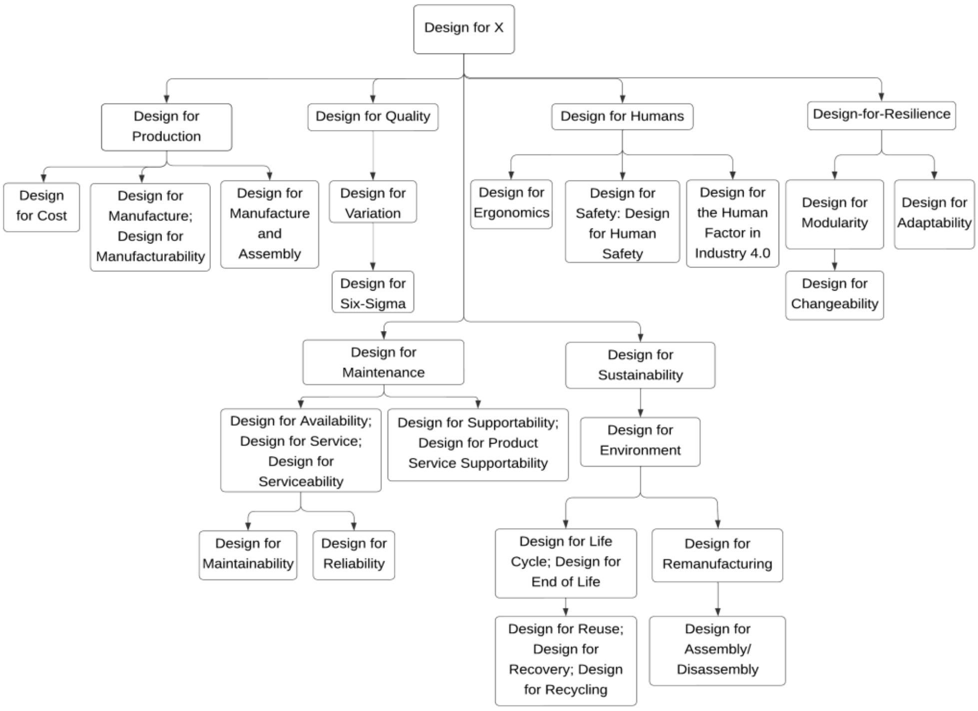

Figure 12: Classification of Design for X methodologies

The choice of these particular DfX methodologies obeys a distinct logic that aligns with classic domains, which are fundamental objectives of Lean methodologies: Production, quality and maintenance, and the emergent domains of I5.0: Sustainability, human-centricity and resilience. Thus, while Lean principles can be connected to all six categories, their strongest association lies with the first three due to their foundational focus on operational efficiency and cost-effectiveness, which are critical drivers in Lean systems (Rahardjo et al. 2023). I5.0 principles, on the other hand, extend Lean's scope by emphasizing human-centricity, sustainability, and adaptability, reflecting the evolving priorities of modern industries.

5.1.1 DfX Methodologies Aligned with Lean Principles

DfX methodologies can effectively support Lean principles by optimizing key manufacturing domains, with each methodology addressing a specific aspect of Lean. In the following, we highlight several DfX methodologies that contribute to advancing Lean objectives.

- **DfX Focused on Product and Process Design**

Design for Production (DfP) estimates the throughput time of a new product (Herrmann and Chincholkar 2001). It evaluates manufacturing system performance (Chincholkar et al. 2003), and provides a holistic picture of the entire manufacturing process with the goal of staying current with product development (Maneschi and Melhado 2010).

Design for Cost (DfC) uses management-imposed cost targets as the main constraints for maximizing competitiveness, or as the main objective under the technical and time constraints; Budget analysis, cost estimation, cost planning, cost control (Sheldon et al. 1991). DfC analyses and evaluates a product's life cycle cost (LCC), then modify the design to reduce the LCC (Xiaochuan et al. 2004). DfC considers three important aspects: Cost types, Design-related and Cost analysis (Mörtl and Schmied 2015).

Design for Manufacture (DfM) focuses on aligning product design with the manufacturing process to achieve optimal results and, ultimately, reduce overall costs (Valentinčič et al. 2007). Design for Manufacturability (DfMy) evaluates product design using a performance ratio based on a set of attributes and criteria, it focuses primarily on the geometrical features of the parts in the design (Das and Kanchanapiboon 2011). Design for Manufacture and Assembly (DfMA) focuses on simplifying parts and product designs to reduce the number of components, lower production costs, enhance reliability and quality, and increase production capacity (Chowdary et al. 2019). The goal is to optimize product assembly by minimizing the number of parts, standardizing fixation types, reducing re-orientation during manual operations, and selecting the most appropriate manufacturing technologies, among other strategies (Formentini et al. 2022).

Design for Quality (DfQ) is a quality-oriented form of integrated product and process development, but the focus is on functionality rather than manufacturability (Morup 1992). DfQ focuses on designing robust products that enhance quality and reliability, minimizing the impact of potential variations during manufacturing and in the product’s operating environment. The aim is to continuously improve product reliability, performance, and technology to exceed customer expectations (Kuo et al. 2001).

Design for Six-Sigma (DfSS) focuses on delivering new products and services that meet high-performance standards, as defined by customer satisfaction and critical quality measures (Jenab et al. 2018). As a key component of DfQ, DfSS employs a structured methodology that utilizes statistical tools to design new products and processes, aiming to minimize defects and process deviations (Sithole et al. 2021).

Design for Reliability (DfR) refers to a set of tools that guide the design of products and processes to ensure that customer reliability expectations are consistently met throughout the product's life, while minimizing overall life-cycle costs (Mettas 2010). DfR is used to affect design for positive improvement in product reliability by using knowledge of failure physics to design out potential problems (Crowe and Feinberg 2017).

- **DfX Focused on Machines and Systems Design**

Design for Maintenance (DfMa) aims to design machines or products to improve ease of maintenance, by adapting them to the specific functions they perform. This ensures that operations can be carried out at reduced cost and in much less time than would otherwise be necessary (Desai and Mital 2006). DfMA aims to influence maintenance activities during the design phase of new systems. Three categories of design for maintenance exist: maintainability, reliability and supportability (Vaneker and van Diepen 2016). Design for Maintainability (DfMy) means designing the system in such a way as to find the optimum balance between investment cost and maintenance cost (Tortorella 2015). DfMy means designing equipment to ensure that it can be repaired quickly and easily (Vaneker and van Diepen 2016).

Design for Supportability (DfSu) focuses on evaluating all aspects of product support, including service, maintenance, and repair, during the design stage, and establishing a strong connection between technical features and additional services for the customer (Goffin 2000). DfSu aims to taking these aspects (service, maintenance, repair) into account during the design process, as support plays a major role in the post-production stages of a product's lifecycle, and generates additional revenue (Arnette et al. 2014). Design for Product Service Supportability (DfPSS) focuses on providing a solution that is easy to assemble, manufacture, and test, incorporating concepts of quality, modularity, and customization to enhance its availability even beyond the manufacturing phase (Sassanelli et al. 2016).

Design for Availability (DfA) enables manufacturers and their customers to efficiently produce and utilize capital equipment that meets stringent system availability standards in a cost-effective manner. Implementing DfA involves two key steps: 1) analyzing the current system availability status, and 2) evaluating the lifetime costs associated with this status of system availability (Smets et al. 2012).

Design for Service (DfSv) involves the planning and organization of people, infrastructure, communication, and hardware components necessary for delivering a service. It focuses on ensuring that maintainability and reliability are prioritized, as these are the most critical factors influencing the serviceability of products (Benabdellah et al. 2019). Design for Serviceability (DfSy) focuses on the ability to perform maintenance and service tasks efficiently. "Serviceability" refers to the ease with which a system can return to normal operation during maintenance interventions, minimizing downtime and ensuring smooth functionality (Gobbo Junior and Borsato 2021).

Design for Variation (DfV) focuses on producing probability distributions of component or system performance characteristics by explicitly considering all sources of uncertainty and variability, including engineering model uncertainty. This approach allows for the calculation and management of risks related to meeting requirements by making design, material, or process adjustments that directly address sources of uncertainty and variability (Reinman et al. 2012).

These DfX are important approaches applied from the design phase to ensure that the final products and systems are optimized in terms of production, quality, cost, maintenance, and other specific criteria. However, it's important to highlight some limitations when they are used in isolation. For instance, focusing on a single criterion, such as cost reduction, may sometimes undermine other aspects like quality or reliability. Additionally, these approaches tend to address criteria separately, which can make it challenging to take a holistic view of the interactions between different goals. This leads us to the complexity of defining specific requirements for Design for Lean, which, unlike traditional DfX, requires a multi-criteria approach. The challenge lies in simultaneously considering multiple factors such as process efficiency, waste reduction, flexibility, and system adaptability, while also integrating sustainability, resilience, and human-centric requirements.

In the following section, we present the DfX methodologies aligned with I5.0 principles.

5.1.2 DfX Methodologies Aligned with Industry 5.0

Although DfX methodologies are often considered traditional, many DfX approaches align with and support the emerging principles of I5.0. These methodologies, originally developed to optimize specific aspects of design and manufacturing, are now proving their adaptability in addressing modern challenges. Below, we present these methodologies, which have been grouped into three main categories that align with the principles of I5.0: Sustainability and End-of-Life, Human Factors and Safety, and Resilience and Adaptability.

- **Sustainability and End-of-Life**

Design for Sustainability (DfS) aims to apply parts of life cycle thinking to products to make them more sustainable (social, economic, and environmental) (Clark et al. 2009). It encompasses four innovation levels: the product design innovation level, which includes Green design, eco-design, Emotionally durable design, and Design for sustainable behavior, among others; the product-service system innovation level, focused on reducing environmental impacts of products and processes; the spatio-social innovation level, which involves Design for social innovation and Systemic design; and the socio-technical system innovation level, aimed at facilitating social change without technological change as a prerequisite (Ceschin and Gaziulusoy 2016).

Design for Environment (DfE) encompasses a broad spectrum of product development activities aimed at reducing environmental impacts. This includes selecting sustainable materials, minimizing environmental effects during the product's use phase, designing for energy efficiency, reducing industrial waste during manufacturing, planning for end-of-life disposal, enhancing packaging, and eliminating harmful substances (Rose 2000). The fundamental principle of DfE is the integration of environmental considerations from the early phases of the product and process design (Jackson et al. 2016).

Design for Life Cycle (DfLC) considers every phase of a product's life, from initial design through its use to its eventual disposal (Newcomb et al. 1996). Design for End of Life (DfEoL) focuses on integrating end-of-life strategies early in the design process, fostering both system innovations and technical incremental improvements or redesigns. The three most prominent end-of-life treatments are Reuse, Recondition, and Recycle (Peeters and Dewulf 2012).

Design for Reuse (DfRu) focuses on creating new architectures that are adaptable to emerging technologies and flexible to evolving requirements (Cohen 1998). Design for Recovery (DfRc) strives to develop products that are both environmentally compatible and commercially viable, contributing to the prevention of environmental issues before they occur (Navin-Chandra 1994). Design for Recycling (DfRe) aims to simplify product recycling, enhance output, and consider product disassembly during the recycling process (Hultgren 2012).

Design for Remanufacturing (DfRem) is a design approach that enables products to be efficiently remanufactured by identifying and preventing inefficiencies in the process. It enhances remanufacturing efficiency by reducing disassembly and reassembly times, as well as inspection and evaluation costs, specifying materials and shapes suitable for repetitive remanufacturing, and incorporating core return mechanisms into the product or component (Charter and Gray 2008). DfRem requires designers to consider each stage of the remanufacturing process and anticipate how design choices will impact these stages (Hatcher et al. 2011).

Design for Assembly/Disassembly (DfAD) focuses on optimizing products for easier assembly and disassembly, taking into account the ease of repair, maintenance, and recycling. It also emphasizes the restoration of parts from end-of-life or rejected products to reduce environmental impact and pollution (Battaïa et al. 2018).

- **Human Factors and Safety**

Design for Humans (DfH) in I5.0 context, must go beyond physical human Factors to take into account the psychosocial effects of technology use and the interactions between humans and technology (Grosse et al. 2023).

Design for the Human Factor in I4.0 (DfHFinI4.0) emphasizes placing the human factor at the center of I4.0, focusing on understanding and optimizing the interactions between humans and technological elements, such as equipment and information systems. This approach ensures that the human aspect is integrated effectively into the technological landscape of I4.0 (Suarez-Fernandez de Miranda et al. 2020).

Design for Safety (DfS) focuses on identifying components, design parameters, and functional requirements of a system, while defining the associated hazards for each. The goal of DfS is to ensure that systems are robust and reliable to meet safety objectives, starting from the design phase (Sadeghi and Tricot 2013a; Sadeghi et al. 2013b). DfS integrates safety knowledge into the design process, identifying and assessing hazardous conditions (Sadeghi et al. 2015).

Design for Human Safety (DfHS) focuses on determining the modes of human intervention within a system, clarifying the levels of intervention, and identifying how tasks are divided between the technical system and the user (Hasan et al. 2003). DfHS is closely associated with human-machine interaction and accident prevention in work environments. Its goal is to examine the variability of the key components, humans, machines, and their surroundings, along with the potential interactions between these components (Sadeghi et al. 2016).

Design for Ergonomics (DfE) aims to adapt systems, organizations, tasks, machines, products, and environments to human physical and mental capabilities (Houssin et al. 2006). DfE was initially aimed at ensuring and communicating high levels of safety and usability for products and services. It then evolved to prioritize the overall user experience, highlighting the quality and significance of interactions between users and the product, environment, or service, whether physical or virtual. In recent years, ensuring that products are safe, intuitive, enjoyable, and easily understandable has become a crucial factor for achieving market success (Tosi 2020).

- **Resilience and Adaptability**

Design for Resilience (DfRs) requires rapid adjustment of production resources through task reallocation and rebalancing (Gu et al. 2015). DfRs reduces complexity of a system by exploiting commonality among its components. Delayed product differentiation reinforces the design-for-resilience strategy through the repurposing products to address modified needs while retaining the majority of their original configuration, and swiftly responding to demand growth within a short timeframe by utilizing an inventory of the main product configuration (Kusiak 2020).

Design for Modularity (DfMo) focuses on creating a variety of products by combining modular components during the product design phase. It involves producing different products by using standard components and sharing common assembly operations for parts of their structure (Kuo et al. 2001). DfMo aims to design loosely coupled interfaces that allow modules to be varied within the product to facilitate component exchange and sharing (Benabdellah et al. 2019).

Design for Changeability (DfCh) aims to design systems and products in such a way that future engineering changes can be easily and quickly implemented, or even avoided. Changeability can be achieved through the principles of simplicity, independence, and modularity (Iakymenko et al. 2022).

Design for Adaptability (DfAd) focuses on creating products as dynamic, flexible systems that can adjust to changes. It enables products to be modified, reconfigured, or upgraded to meet evolving market demands, adapt to new technologies, or address physical or economic factors (Kasarda et al. 2007).

Existing DfX methodologies often concentrate on optimizing a single criterion, limiting their ability to tackle the complex and multifaceted challenges faced by modern industries. While DfX can enhance specific aspects of a product or process, it often neglects other critical factors. As industries shift towards I5.0, which emphasizes balancing technological advancement with human-centric considerations, sustainability, and resilience, there is a clear need for a new framework that integrates Lean principles with these I5.0 priorities. Our work combine Lean's efficiency with I5.0's core values. Traditionally, companies focused on a limited set of criteria when designing their manufacturing systems. However, to achieve a high-performance system, it is essential to consider a broader range of criteria that collectively enhance overall performance. The first step of our aim of designing a high-performance system requires us to take into account as many criteria as possible that contribute to improving the performance of the systems we intend to design. We aim to ensure that the designed systems not only meet immediate operational requirements, but also adapt to future challenges.

We focus on the identified DfX methodologies to extract a set of common criteria/domains related to Lean and I5.0 concepts. These criteria are fundamental for guiding the extraction of Lean requirements and parameters, which will be discussed in the next chapter.

5.2 Lean/Industry 5.0 and Axiomatic Design

When faced with a complex challenge in industrial practice, engineers typically break it down into smaller problems and attempt to maintain independent solutions for each of these smaller problems. Therefore, a useful approach that offers directives for breaking down complicated issues as well as autonomous mappings from issues to solutions is required. Axiomatic Design (AD) provides a mechanism for such decomposition (Hachicha et al. 2008). In the following sections, we introduce the AD method and analyze its utilization in modeling Lean and I5.0 principles.

5.2.1 Axiomatic Design Method

Axiomatic Design (AD), introduced by Suh (1990), provides a scientific framework for the design process and is considered one of the most promising approaches to solving complex problems in manufacturing systems. The primary goal of AD is to establish a scientific foundation for design, enhancing the design process by offering designers a theoretical framework that incorporates logical and rational thinking, along with useful tools (Suh 1990; Suh and Suh 2001). AD views design as the synthesis of solutions, manifested in products, processes, or systems, aimed at meeting perceived needs by correlating Functional Requirements (FRs) with Design Parameters (DPs). (Houshmand and Jamshidnezhad 2006) present an enhanced model of AD, shown in Figure 13. In this model, the FRs in the functional domain represent the design goals or objectives, while the DPs in the physical domain define how these FRs must be satisfied. The DPs are achieved through the proper selection of Process Variables (PVs), which can be understood as the tools, methods, and resources necessary to meet the design objectives. The zigzag approach not only decomposes FRs and DPs but also establishes a hierarchy that details the design process (Kose et al. 2022). As illustrated in Figure 13, the design domains start with the customer domain, which houses the initial customer requirements. These requirements are then translated into a set of independent FRs in the functional domain, which also introduces constraints that must be respected throughout the design process. These constraints are applied to the FRs, DPs, and PVs. The mapping of FRs to the physical domain and the connection of DPs to the process domain via PVs are depicted in the Figure 13.

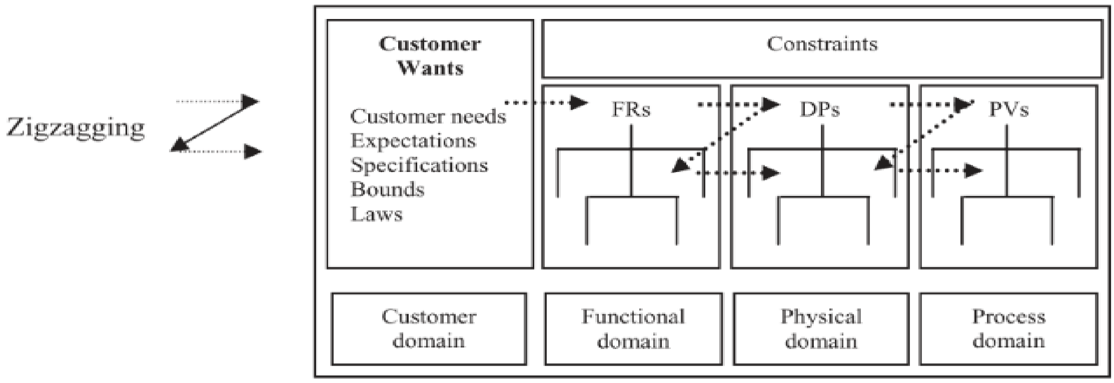

Figure 13: Axiomatic Design Model (Houshmand and Jamshidnezhad, 2006)

The key concept in AD revolves around two fundamental design axioms: the Independence Axiom and the Information Axiom.

- **Axiom 1. Independence Axiom**

In an optimally designed system, the relationship between FRs and DPs is structured so that each requirement is satisfied independently, without affecting any other requirement. This relationship between FRs and DPs is mathematically represented as:

$$(FR)= |A|\ (DP) \qquad (1)$$

where (FR) is the FR vector, (DP) is the DP vector and |A| is the design matrix (DM) that characterizes the design.

To meet the Independence Axiom, the DM should be either diagonal or triangular. This ensures that the relationships between FRs and DPs are either uncoupled or decoupled, which are considered desirable or acceptable in AD. In an uncoupled design, ideally preferred, the DM is diagonal, indicating that each FR is independent and can be satisfied solely by adjusting its corresponding DP. In a decoupled design, the matrix is triangular, which means that while some FRs and DPs are interdependent, the design can still manage these relationships effectively. In coupled designs, DPs can influence FRs in an unpredictable manner, often necessitating multiple design iterations to modify previous designs. As a result, the designer must aim to transform a coupled design into an uncoupled or, at the very least, a decoupled design. Figure 14 represents the three types of DM.

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} X & & \\ & X & \\ & & X \end{bmatrix} * \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix} \qquad \begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} X & & \\ & X & \\ & X & X \end{bmatrix} * \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix} \qquad \begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} X & & X \\ & X & \\ & X & X \end{bmatrix} * \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix}$$

Uncoupled Design   Decoupled Design   Coupled Design

Figure 14: Types of Design Matrices

- **Axiom 2. Information Axiom**

The Information Axiom focuses on minimizing the information content in a design, which in turn reduces uncertainty and complexity. This principle states that, among all possible solutions that fulfill the Independence Axiom, the optimal design is the one with the least information content. Essentially, the design should be as simple and efficient as possible, requiring fewer resources, decisions, or adjustments to meet the desired FRs.

With an understanding of the AD method, the following section highlights its significance in modeling Lean and I5.0 systems/ principles.

5.2.2 Axiomatic Model for Designing Lean and Industry 5.0 Principles

From one standpoint, some works has tried to use AD to propose a model of Lean as a global philosophy. (Houshmand 2002) develop a hierarchical structure for conceptualization of Lean philosophy. According to the author, the three essential foundations of Lean manufacturing are organizational capabilities, technological capabilities and value chain analysis. The proposed procedure has been implemented in a car manufacturer company. (Houshmand and Jamshidnezhad 2006) present an Axiomatic modeling of Lean production system design, using process variables (PVs). (Vinodh and Aravindraj 2012) propose an Axiomatic model of Lean manufacturing system design that provides a scientific framework for the concepts, principles, and methodologies of Lean manufacturing. They identify and formulate the relationship between FRs, DPs, and PVs in the Lean manufacturing system of a rotary switches manufacturing organization.

Some other works has tried to apply AD only on one principles of Lean. (Hachicha et al. 2008) provide a framework for the complete Cellular Manufacturing system design. It combines AD and Experimental Design to generate several feasible and potentially profitable designs. (Kabadurmus and Durmusoglu 2020) propose a holistic approach for pull production control system design using AD. (Kose et al. 2022) develop a framework for designing Autonomous Maintenance, a key pillar of TPM, incorporating preliminary, reactive, preventive, and proactive steps through the AD. The proposed design was validated by applying the roadmap to a textile manufacturing system..

From another standpoint, few papers has tried to highlight the importance of using AD to modeling I4.0 and I5.0 principles. (Brown and Rauch 2019) explore ways to enhance creativity and sustainability within AD processes, demonstrating how AD theory and methods can refine the selection process in evolution-inspired creativity. They focus on formulating FRs, generating, and selecting DPs, with I4.0 serving as a practical example of this approach. (Rauch and Brown 2021) demonstrate how to teach the AD of manufacturing processes and systems in SMEs, aiming to achieve long-term sustainability through the integration of I4.0. (Cochran and Rauch 2020) propose an approach to more effectively address sustainability and I4.0 from a long-term strategic perspective. They emphasize the significance of applying well-established Axioms from AD to manage complexity and improve enterprise design. (Agote-Garrido et al. 2023) propose utilizing the Value Sensitive Design (VSD) methodology to redesign manufacturing workplaces in alignment with the values set by I5.0. They suggest a design approach that incorporates the goals of I5.0 into the development processes of new technologies, using the AD method. (Leng et al. 2024) review the evolution of Manufacturing System Design (MSD), including the AD method, in the context of I4.0 and I5.0. They identify the challenges and outline future research directions for the progression of MSD towards I5.0.

Based on this literature review, we deduce that, on one hand, there is a notable lack of studies utilizing AD to model Lean production or manufacturing systems, including their tools and principles. Most existing research has focused mainly on the application of Lean principles to existing systems, with an emphasis on the organizational, strategic and managerial aspects of Lean production. On the other hand, articles seeking to integrate AD with I4.0 and I5.0 concepts have mainly emphasized the importance of using AD to design complex systems that integrate both paradigms, although practical applications remain limited. In addition, there is an absence of works has attempted to design a system that integrates both Lean and I5.0 principles using AD, which can be considered as a fundamental proposal that must be developed further to provide more details relevant for different domains.

- *Seventh Gap: Absence of an Axiomatic model for designing a system that integrates Lean tools in alignment with I5.0 principles*

While Axiomatic Design provides a structured approach to modeling Lean systems, it does not explicitly address contradiction resolution. To further enhance problem-solving capabilities, we explore in the following section the relationship between Lean and TRIZ.

5.3 Lean and TRIZ

With the aim of optimizing the design of manufacturing system, a literature review is conducted to determine the potential contribution of TRIZ to facilitating the integration of Lean tools and functionalities during the design phase by solving potential contradictions. This scientific exploration seeks to clarify how TRIZ can enhance and align Lean principles and functionalities to achieve optimal and efficient manufacturing system design. The main theme that predominates in the literature on the relationship between Lean and TRIZ is that both methodologies share the same fundamental principle: to design and delivers customers with the products they really want, using principles and tools to reduce waste or minimize the use of new resources, both concepts use a continuous improvement procedure. This section focuses on a comparative analysis of the common features of Lean and TRIZ concepts.

The following works illustrate the similarities between these two concepts: (Ikovenko and Bradley 2004) identify how TRIZ Plus can be used in the five stages of Lean Thinking. (Bligh 2006) describe the overlap Between TRIZ and Lean. According to the authors, TRIZ focuses on individual elements to be optimized, while lean takes into account the whole system to find potential efficiencies. The similarities are not limited to the system level. Many TRIZ elements have a Lean equivalent. (Aggarwal et al. 2008) discuss the similarities between Toyota Production System and TRIZ, the authors show how the management techniques and manufacturing systems employed by Toyota are derived from TRIZ principles.

Other articles show how the combination of TRIZ and Lean can improve other perspectives. (Navas and Machado 2015) examine the “lifeline” of technical systems in a Lean environment and how TRIZ may be used to provide organizations with tools to determine the best way for all “old stages” of technical systems. According to the authors, combining TRIZ with Lean approaches allows companies to manage their products more effectively throughout their lifecycles, resulting in improved product end-of-life and recycling management. (Bashkite and Karaulova 2012) propose a methodology to facilitate the understanding of the TRIZ methodology for combination of Green and Lean practices. (Navas and Machado 2013) integrate TRIZ analytical tools with Lean techniques, to assure the sustainability of production system management. (Harrington 2017) propose an inventive method for improving or modifying the design by combining Lean and TRIZ. His method is based on the TRIZ 39×39 contradiction matrix. He uses a "41 × 3" matrix, with the three parameters: quality, cost and productivity.

One of the main axes in the research works focus on how TRIZ can improve Lean applications. (Kumaresan and Saman 2011) integrate changeover techniques of SMED with TRIZ to counter problems like non standardized and non-optimized practices in the current changeover process. In their case study of a semiconductor company, the integration of these techniques reduced changeover time from 240 minutes to 32 minutes. (Sousa et al. 2014) propose TRIZ-Lean mixed methodology in the maintenance service to reduce or eliminate the identified waste. Despite the absence of specific guidelines on the application of the general solutions proposed for each tool, the authors assert that these solutions can be applied to tools such as 5S, Kaizen, PDCA (Plan-Do-Check-Act), TPM, Autonomous Maintenance and VSM. (Cabrera and Li 2014) propose an optimization cycle that complements the principles of Lean and TRIZ as an alternative to improve the efficiency of resources. The authors used the Lean tool VSM to assess issues and waste in production, and the principles of TRIZ to develop innovative solutions for the most contradictory problems, leading to improvements in the initial VSM. (Dewi et al. 2013) propose to design a work environment using the 5S method and make arrangement of equipment and working tool cabinet design with TRIZ methods. In this paper, the improvement of the 5S tool is based on the design of equipment racks using TRIZ methods.

Few works have attempted to use TRIZ to integrate Lean tools and functionalities from the early design phase. (Slim et al. 2021b) propose an approach, based on Lean and Inventive Design Methodology (IDM-TRIZ), to identify and resolve the contradictions due to the Lean integration and provide innovative technical solutions. The approach is illustrated by the integration of the functionalities of SMED and the 5S method from the early design phase. The authors propose a case study about the “3D printer clogged nozzle” outlines the feasibility of their proposed approach. According to the authors, the integration of Lean functionalities from the early design phase may be a cause of some contradictions for a variety of reasons, including system performance and user considerations.

Based on this literature review, we deduce that previous research has mainly focused on the use of TRIZ to improve individual Lean tool in existing systems, where TRIZ is frequently used to solve problems that arise when implementing these tools. The focus has been on a limited set of Lean tools, such as SMED and 5S. However, there is a significant lack of research work on the integration of the requirements of other essential Lean tools, such as JIT, VSM, Kanban, Poka-Yoke, TPM and Heijunka. Moreover, few papers have explored the integration of multiple Lean requirements during the design phase, in order to identify and address potential contradictions that may result from this integration.

Compared to the existing literature, which focuses mainly on the use of TRIZ to improve individual application of Lean tools, most often SMED and 5S, and the notable absence of studies analyzing the relationship between TRIZ and other essential Lean tool requirements, we observe a significant gap. Specifically, there is a lack of research aimed at using TRIZ to integrate multiple Lean tool requirements and resolve contradictions that may arise between Lean requirements themselves. In this work, we address this research gap by proposing a new methodology aimed at integrating multiple Lean tool requirements from the design phase in an I5.0 context. Our approach focuses on identifying, extracting and resolving the various contradictions that may arise due to the integration of Lean requirements. By integrating Lean requirements from the beginning and analyzing possible contradictions, we focus on preventing potential problems before they arise, rather than resolving them once the system is installed.

- *Eighth Gap: Absence of methodologies aimed at identifying and resolving contradictions that may arise from integrating multiple Lean requirements during the design phase*

We identify eight gaps across different axes addressed in our review. Table 3 summarizes these gaps along with our contributions.

Table 3: Summary of Gaps from the Literature and Corresponding Contributions

Gaps from the Literature	Contributions
First Gap: The focus of integrating Lean into the design is on improving the design process itself, with limited research on the integration of Lean to enhance the designed system that is the subject of the design process	Our work addresses the improvement of the performance of the system being designed, rather than the design process, by integrating Lean requirements in an I5.0 context to fulfill multiple performance criteria.
Second Gap: Ambiguous understanding of Lean requirements and a lack of guidelines for integrating Lean requirements and parameters during the design phase	We define Lean requirements to address manufacturing process issues and propose a new perspective where Lean requirements bridge the gap between existing system limitations and optimal, performance-driven future designs. Our work provides a list of over 100 Lean requirements extracted from the literature, along with their corresponding parameters, covering both classic and I5.0 domains. We identify the limitations of applying Lean tools in existing systems and derive Lean functional requirements to be integrated from the design phase, aiming to reduce the need for Lean interventions in future system designs.
Third Gap: Studies aiming to integrate I5.0 from the design phase, although limited in number, tend to address its principles separately, with limited existing research focusing on the integration of all three main principles of I5.0	In our work, we integrate Lean requirements with the three fundamental principles of I5.0, while also identifying I5.0 technologies that support this integration.
Fourth Gap: Lack of empirical studies evaluating the integration of Lean 4.0 tools from the design phase of manufacturing systems	We presented empirical evidence, derived from a questionnaire survey supported by exploratory and confirmatory factor analysis, that highlights the impact of incorporating Lean 4.0 tools during the design phase across five critical design dimensions. The complete details of this contribution are published in (Gdoura et al. 2024a).
Fifth Gap: Lack of analysis on the relationship between Lean tools and the fundamental principles of I5.0	We analyze how Lean has previously addressed sustainability, resilience, and human-centricity, even before the official introduction of the I5.0 concept. This analysis enables us to understand how Lean inherently incorporates these principles, independent of the technological advancements highlighted in I5.0.
Sixth Gap: Absence of guidelines and methodologies for formulating and integrating Lean tools added values during the design phase of manufacturing systems in an I5.0 context. Seventh Gap: Absence of an Axiomatic model for designing a system that integrates Lean tools in alignment with I5.0 principles	We propose an Axiomatic model comprising three main facets: “Design a Sustainable Lean Manufacturing System”, “Design a Resilient Lean Manufacturing System”, and “Design a Human-Centric Lean Manufacturing System”. This model serves as a guideline for aligning various Lean tool requirements with I5.0 principles and integrating them into the design of manufacturing systems, while also identifying the design parameters and process variables to be considered in this integration.
Eighth Gap: Absence of methodologies aimed at identifying and resolving contradictions that may arise from integrating multiple Lean requirements during the design phase	We propose a new methodology called “Lean 5.0 Parameter Integration Matrix”, which is based on parameters identified from the literature and those derived from the Axiomatic design model. This methodology facilitates the integration of multiple Lean 5.0 requirements into various system designs and enables the simultaneous formulation and resolution of contradictions between different requirements.

Conclusion

This chapter presents a diversified literature review to identify gaps in the existing literature regarding the relationship between Lean and I5.0, their integration in systems design, and the combination of these concepts with TRIZ and the AD method.

In the next chapter, we present our methodology for designing a Lean 5.0 system, based on the AD and TRIZ methods. Furthermore, we propose a set of Lean requirements and parameters aligned with I5.0 principles. In addition, we propose a generalized Axiomatic model that favors the proactive aspects of Lean 5.0 requirements integration, in which we identify the appropriate combination of Lean tools and I5.0 principles to meet multiple performance criteria.

Chapter III: A New Methodology for Inventive Lean 5.0 Manufacturing Systems Design

Introduction

Manufacturing companies are used to apply Lean tools to eliminate waste in manufacturing processes. The conventional view is that many companies realize the importance of implementing Lean tools when they notice defects and waste at the manufacturing phase. These tools have added value in achieving the required performance. However, waiting for these problems to occur before taking action is a reactive approach that can lead to additional costs and significant disruptions such as production stoppages, equipment modifications, or the installation of new equipment. Additionally, it may require changes in employee behavior and workflows, as workers might need to adapt to new procedures under pressure. We propose a better strategy to integrate the value-added benefits of Lean tools from the design phase of manufacturing systems, thus anticipating and preventing problems before they arise. To design a system with the desired performance from the beginning, it is essential to change perspective and move from a reactive or curative to a proactive and preventive approach. The integration of Lean requirements from the design phase offers a more effective solution by optimizing operations from the beginning and reducing the need for major improvements in the manufacturing phase. Additionally, we aim to align this integration with the principles of Industry 5.0 (I5.0) to support the contemporary values and requirements needed today including environmental issues, companies resilience to frequent disruptions, and the importance of human roles in the system.

Our aim to improve industrial performance consists of analyzing the challenges of integrating Lean tools into existing systems, identifying the various requirements, and proposing a guideline to integrate these requirements in an I5.0 context to design high-performance systems.

In this chapter, we introduce the Lean 5.0 paradigm and present our methodology for integrating Lean requirements within an I5.0 context from the design phase. Additionally, we develop our Lean 5.0 Axiomatic model that combines Lean tool requirements, derived from the limitations of Lean tool applications in existing systems, with the principles of I5.0.

1. Framework of the Proposed Methodology

Our objective is to introduce a new Lean 5.0 paradigm that integrates the added value of Lean tools from the design phase, overcoming the constraints and challenges of their implementation in existing systems while addressing the limitations of Lean 4.0 by aligning this integration with I5.0 principles.

Lean 5.0 could be considered as an advanced evolution of Lean Manufacturing that integrates Industry 5.0 (I5.0) principles, emphasizing human-centricity, sustainability, and resilience while leveraging smart technologies. Lean 5.0 builds upon traditional Lean principles by enhancing human-technology collaboration, promoting eco-friendly and adaptable systems, and optimizing real-time digital integration for improved decision-making. Figure 15 illustrates the framework for the proposed Lean 5.0 paradigm.

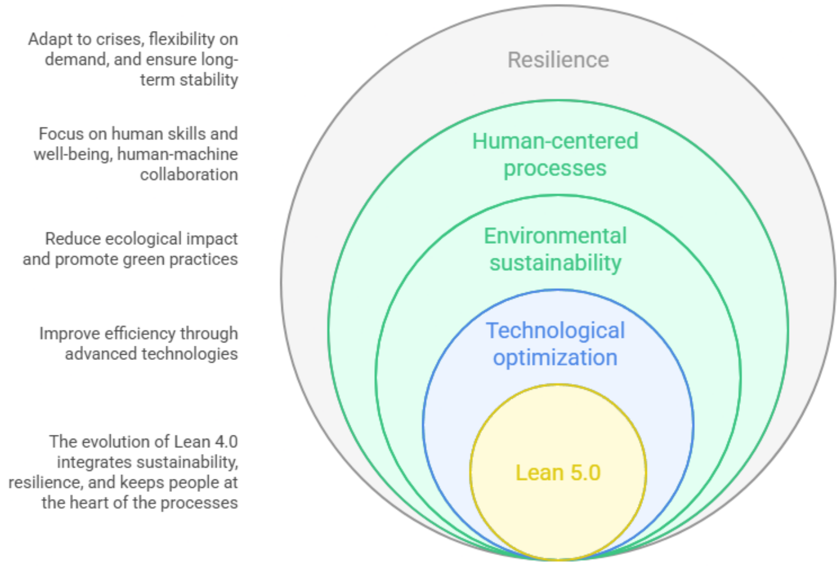

Figure 15: Lean 5.0 Framework

By embedding these principles from the design phase, Lean 5.0 enables flexible, sustainable, and highly responsive manufacturing systems that balance automation with human expertise, ensuring both efficiency and adaptability in the face of modern industry challenges. This integration leads us to propose a methodology we refer to as "Design for Lean 5.0", which embeds Lean requirements early in the design process, overcoming the challenges and limitations of implementing them in existing systems. This approach also addresses the shortcomings of Lean 4.0 by aligning Lean requirements integration with I5.0 principles. Figure 16 illustrates the framework of our proposed approach.

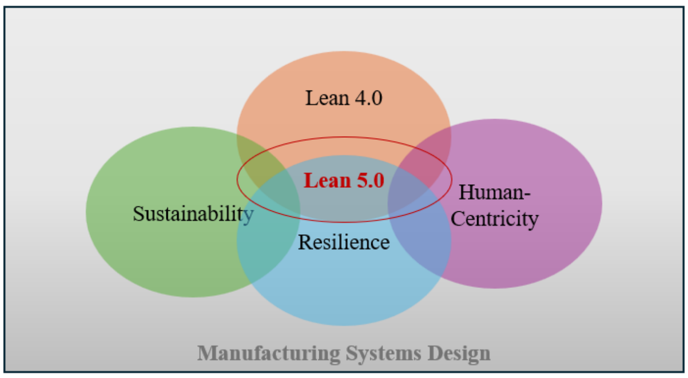

Figure 16: Design for Lean 5.0 Baseline

To effectively integrate Lean requirements within an I5.0 context from the design phase and address the limitations of Lean tool applications in existing systems, we propose a structured methodology for the early incorporation of these requirements to meet multiple performance criteria. Furthermore, we identify and analyze potential contradictions that may arise from this integration. Our methodology emphasizes overall performance, considering both process efficiency and user experience.

Building on the aforementioned design methods to support the design process discussed in the previous chapters, we analyze their synergy and complementarity with the goal of combining their strengths into a single comprehensive methodology. The objective is to enhance the performance of manufacturing systems by integrating Lean requirements within an I5.0 context, starting from the initial design phases. To achieve this, we leverage the synergies between Lean and TRIZ, as well as the effectiveness of Axiomatic Design (AD) in decomposing complex systems.

Figure 17 presents the overall framework of the proposed methodology in the form of a V-Model, which follows a top-down approach based on the Function-Behavior-Structure (FBS) model, ensuring continuous refinement and improvement of the manufacturing system through four iterative steps: Requirements specification, conceptual design, embodiment design, and detailed design.

By utilizing FBS, designers can clearly delineate the Functional Requirements (FRs) that TRIZ seeks to address through inventive solutions while ensuring that the Design Parameters (DPs) identified in AD are effectively realized in practice. This comprehensive approach allows for a more holistic understanding of how to resolve contradictions and optimize designs, ultimately leading to inventive and efficient solutions. Furthermore, FBS serves as a bridge between the abstract concepts of TRIZ and the practical applications of AD, facilitating a cohesive design strategy that aligns functional objectives with structural realities. In this context, the FBS framework could be an important tool for integrating TRIZ and AD, ensuring that designs are not only inventive but also functionally coherent and systematically realizable.

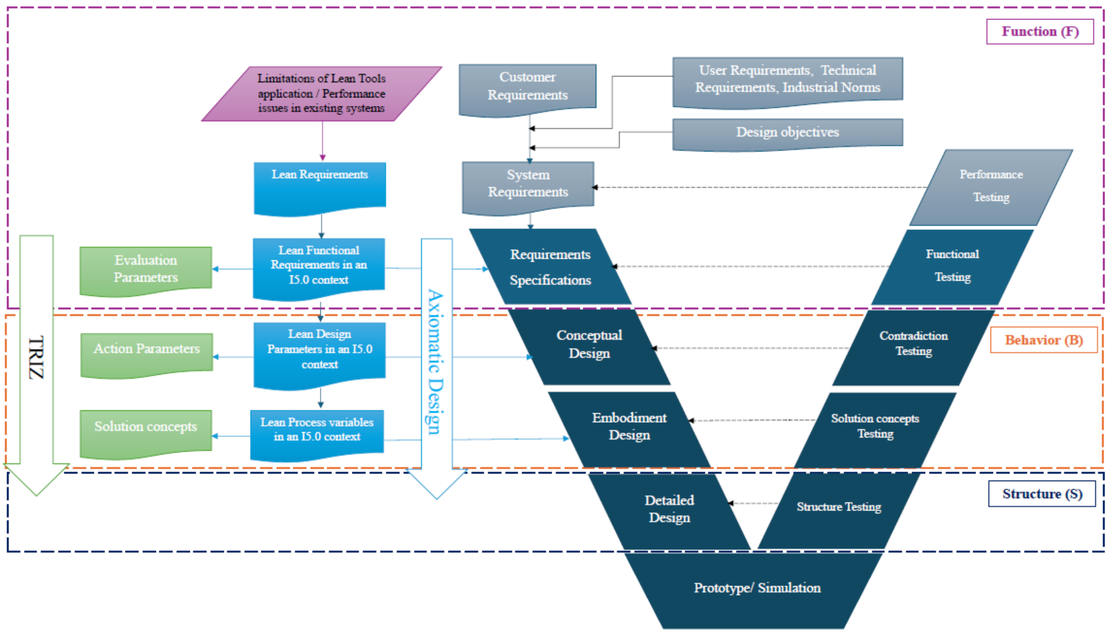

Figure 17: Framework of the Proposed Methodology "Design for Lean 5.0"

The first phase, corresponding to the function element of the FBS framework, focuses on defining system requirements by identifying the limitations of Lean applications in existing systems and evaluating performance challenges. This process helps determine the relevant Lean requirements. Since multiple requirements may be identified, companies must prioritize them based on their strategic objectives and align them with design goals. Once the Lean requirements are selected, different approaches for aligning them with I5.0 principles must be analyzed to effectively address specific performance objectives. This analysis ensures that the integration of Lean and I5.0 is coherent and strategically beneficial. The outcome of this first phase is a set of well-defined FRs that serve as a foundation for designing a Leanless system while maintaining alignment with I5.0 principles.

The system's behavior involves identifying the parameters resulting from the combination of Lean FRs and I5.0 principles, as well as the tools and mechanisms that facilitate their integration. The structure of the system can be deduced as the arrangement of components, elements, and relationships required to support and implement the Lean FRs and I5.0 principles. It involves organizing the system's physical and logical components to enable the integration of the identified parameters, tools, and mechanisms. The structure ensures that the system's behavior aligns with its intended technical functions while maintaining coherence with the requirements of Lean and I5.0.

The Design for Lean 5.0 methodology consists of three main phases:

- **Phase 1: Formulation of Lean Requirements and Parameters**

Our methodology starts with identifying various requirements: Customer and User Requirements, Technical Requirements, and Industrial Norms. The second step involves identifying design objectives. In our case, these objectives represent criteria aligned with Lean and I5.0 principles, as identified in the literature review conducted on the 34 DfX methodologies in Chapter II. The third step involves extracting the corresponding Lean requirements from the literature by analyzing Lean concepts that fulfill the identified criteria. This is followed by identifying the parameters corresponding to the extracted requirements (Gdoura et al. 2025).

- **Phase 2: Axiomatic Model for Lean 5.0 Manufacturing Systems Design**

The first step involves identifying Lean FRs that correspond to the added value of Lean tools, and its formulation is based on the limitations of its application in existing systems. The next step is to determine the Highest-Level FR and its decomposition. We propose a generalized Axiomatic model with three main facets, representing the combination of Lean and I5.0 principles: FR1: “Design a Sustainable Lean Manufacturing System”, FR2: “Design a Resilient Lean Manufacturing System”, and FR3: “Design a Human-Centric Lean Manufacturing System”. The decomposition of each of these FRs is guided by the Lean FRs corresponding to eight common Lean tools, allowing them to be integrated from the design phase to avoid reliance on these tools in the operational phase.

❖ Phase 3: Formulate and Resolve Contradictions

TRIZ and AD both effectively address industrial problems, but they serve different purposes. TRIZ is focused on generating inventive solutions, while AD excels in systematically defining problems and analyzing solutions based on two key axioms. AD emphasizes problem definition over solution generation and lacks specific techniques for creating optimal solutions. In contrast, TRIZ centers on generating solutions but relies on defining problems through physical or technical contradictions, which may not always apply to complex, multi-layered issues (Shirwaiker and Okudan 2008).

Combining TRIZ and AD offers a powerful, systematic approach to solving complex design problems, surpassing the capabilities of other design methods. AD provides a clear, structured framework for breaking down design challenges into FRs, DPs and PVs, ensuring that the design is logically sound and meets design requirements while minimizing dependencies. However, AD alone may struggle when faced with inherent contradictions or trade-offs in the design process. This is where TRIZ excels: it focuses on identifying and resolving contradictions by applying inventive principles that encourage inventive, out-of-the-box solutions. By combining these methods, designers benefit from AD’s methodical decomposition of design problems and TRIZ’s ability to resolve contradictions creatively. Together, they create a comprehensive design methodology that enhances both efficiency and innovation, making it more effective than using either method in isolation or other more traditional design methods that lack TRIZ's inventive solutions or AD's rigor in structure.

In addition, we observe that AD and TRIZ share several similarities, which enhance their compatibility when combined. These similarities are highlighted in Table 4.

Table 4: Similarities between TRIZ and AD

AD-TRIZ Relationship	Similarities
Functional Requirements (FRs) - Evaluation parameters (EPs)	Both FRs and EPs represent the design objectives or criteria that guide the solution process. In AD, FRs are the intended functions, whereas in TRIZ, EPs help quantify how well a solution meets those functions or reveals contradictions. FRs in AD are the goals of the design, while EPs in TRIZ evaluate contradictions or performance.
Design Parameters (DPs)- Action Parameters (APs)	DPs in AD and APs in TRIZ both relate to the physical attributes or design choices that are modified to meet the desired outcomes. Both serve as a bridge between abstract requirements and real-world solutions. DPs define the physical solutions in AD; APs in TRIZ are the conflicting elements that need resolution.
Process Variables (PVs)- Solution Concepts (SCs)	PVs and SCs both relate to the implementation stage of the design. PVs focus on the practical aspects of how the design is produced or controlled, while SCs offer creative solutions to resolve contradictions and improve the design. Both sets of concepts involve actions or methods that change/act on the system's physical or operational characteristics to meet the design goals. PVs are the methods used to satisfy DPs, while SCs in TRIZ offer inventive ways to solve problems.

Attempting to integrate several Lean 5.0 requirements into the design of a manufacturing system to satisfy multiple performance criteria may result in contradictions. To formulate and resolve contradictions, we propose a new methodology: "Lean 5.0 Parameter Integration Matrix (L5.0PIM)", to resolve the different types of problems. L5.0PIM contains a set of generalized Lean parameters resulted from our AD model. It allows the identification of technical and physical contradictions that may arise from the integration of multiple Lean 5.0 requirements, and provides guidance for their resolution, using the principles of TRIZ methodology for resolving technical and physical contradictions (Gdoura et al. 2024b).

Figure 18 presents a flowchart that outlines the process for designing manufacturing systems, with the goal of integrating various requirements to ensure alignment between Lean principles, I5.0 considerations, and the unique needs of different customers and companies.

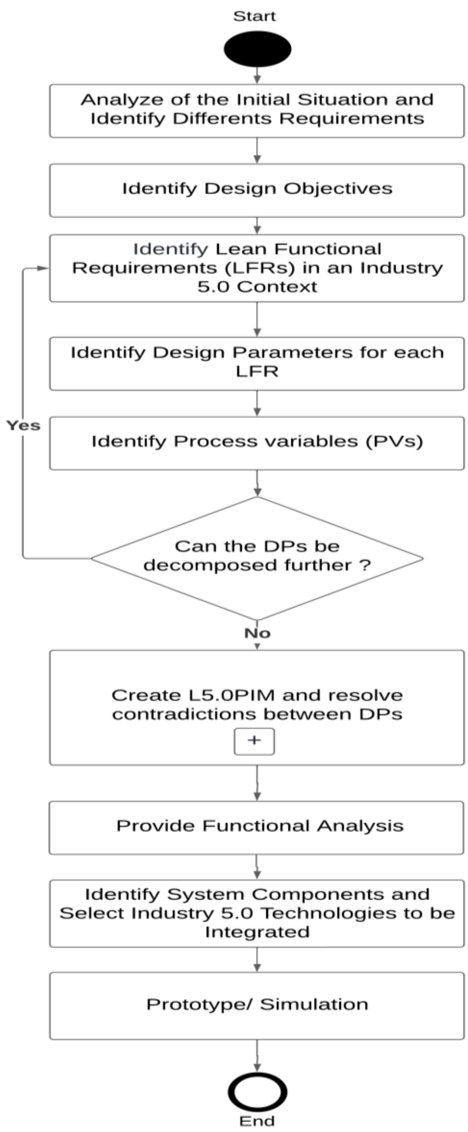

Figure 18: Methodology for Designing Lean 5.0 Manufacturing System

The first two phases will be addressed in the following sections, while the third phase and the step "Create L5.0PIM and resolve contradictions between DPs" are detailed in Chapter IV.

2. Phase 1: Requirements Specifications

The requirements specification phase is the foundation of any successful system design. This is where we confront the problem to be solved and navigate between the different objectives set by stakeholders and designers. We first select the problem categories and corresponding requirements that will guide our solution. Integrating Lean requirements into the design work must starting from the first phase of requirement specification. This early integration has the potential to targeting the following design process to consider Lean tool functionalities improving the overall performance of a system and optimizing the interrelationships among its diverse components.

Below, we present the various requirements to be identified in the design of a new system, which serve as a preparation to guide the selection of the Lean requirements to be integrated.

2.1 System Requirements

We consider that system requirements are composed of three categories: customer and user requirements, technical requirements and industrial standards, and design criteria.

2.1.1 Customer and User Requirements

When designing a manufacturing system, customer requirements and user requirements have distinct objectives. Customer requirements refer to the expectations and needs of the end customer who will receive and use the product or service produced by the system. They focus on the quality, cost, functionality and delivery time of the final product. User requirements, on the other hand, concern the needs of the people who will interact with the manufacturing system itself, such as operators, engineers and maintenance personnel. These requirements focus on aspects such as system usability, safety, efficiency and ease of maintenance, to ensure that the manufacturing system is not only effective in producing the desired results, but also user-friendly and reliable in its day-to-day operation. It is essential to balance both sets of requirements to create a system that satisfies customers while being practical and efficient for users.

2.1.2 Technical Requirements and Industrial Norms

According to (Slim et al. 2021a), the main tasks of engineering design are to determine the most effective technical solution to satisfy a set of requirements and constraints encompassing human, material, technological, economic and environmental factors.

Technical requirements define the specific functionalities, capabilities and performance criteria that the system must meet to efficiently produce the desired performance. These requirements encompass aspects such as: Equipment specifications, energy efficiency, workplace safety, workplace organization, etc. We identified 26 of the most widely recognized performance criteria extracted from literature, aligned with the evolution of production system paradigms. These criteria were categorized into five design target dimensions: Production System (PS) efficiency, PS reactivity, PS durability, PS quality, and PS intelligence. These criteria are presented in Table 5 (Gdoura et al. 2024b).

Table 5: List of Performance Criteria (Gdoura et al. 2024b)

PS efficiency	*PS reactivity*	*PS durability*	*PS quality*	*PS intelligence*
Productivity	Agility	Innovation	Customer satisfaction	Automation
Maintainability	Communication	Re-manufacturability	Quality	Maintainability
Cost	Complexity	Reusability	Usability	Diagnosis
Availability	Flexibility	Sustainability		Human skills 4.0
Reliability	Speed	Inventiveness		Re-configurability
Safety				Smart tools 4.0
				Supplier and customer integration

It is also essential to recognize the various constraints, including budget, time, resources, cultural and ethical considerations, as well as technological limitations. Equally important is compliance with industry norms which encompass standards, guidelines and best practices specific to an industry or sector, and often relate to quality, environmental regulations and safety requirements.

2.1.3 Design Criteria

This step involves the initial selection of key design criteria. Our analysis is based on the criteria known as "Xs", derived from various DfX methodologies. This step will guide the selection of the requirements that the designer aims to integrate. In our literature review in Chapter II, we identified 34 distinct DfX methodologies that satisfy both Lean and I5.0 principles, each focusing on optimizing different aspects of system design. Our aim is to integrate the most relevant performance criteria to improve various aspects of system design. Our selection is based on the common "Xs" cited in the literature. In a design project, the choice of preferred DfX methodologies depends on information gathered from customer and user requirements, as well as technical requirements, and varies according to the nature of the system and the target market.

The identified criteria from DfX methodologies will guide the extraction of the corresponding Lean requirements, as outlined in the following section.

2.2 Lean Requirements and their Corresponding Evaluation Parameters

As indicated in chapter II, the second gap was the *Ambiguous understanding of Lean requirements and a lack of guidelines for integrating Lean requirements and parameters during the design phase*. In the literature, occurrences of the expression "Lean requirements", although rare, are generally accompanied by vague and general statements that lack clarity and are not easily applicable to the design process. However, in response to the current gap of the vague understanding of Lean requirements, we propose a structured guiding methodology for identifying and integrating these Lean requirements into the initial stages of engineering design process. For each Lean requirement, we identify the corresponding evaluation parameters aimed at measuring, controlling, and optimizing critical aspects of the industrial process. These parameters are designed to track performance against targets and objectives, making it easier to identify deviations or areas requiring improvement.

By understanding the specific parameters associated with Lean requirements, designers can make informed decisions on aspects such as process layout and equipment selection, evaluate different design options, and select the one that optimizes performance in relation to the defined objectives. This approach ensures that Lean requirements are explicitly considered and respected.

When designing a new manufacturing system, it is often complex to estimate precisely the list of Lean requirements to be integrated in the early design phases. At this phase of the requirements specification, detailed information on equipment and production flows is generally lacking. In the face of this uncertainty, a preliminary analysis can be carried out based on initial data, informed assumptions and historical data from similar systems, industry standards or competing models. These assumptions could then be adjusted and refined as more specific and detailed information becomes available, enabling Lean requirements to be better adapted to the system under design. However, with the absence of historical data qualitative assessment can be made based on industry knowledge and experience with similar systems.

In our research, we emphasize the importance of articulating Lean requirements that directly target identified issues in the manufacturing process, starting from the requirement specification phase. In this context, we propose a new vision that conceptualizes Lean requirements as the gap between the undesirable current state where the application of Lean in existing systems faces various barriers and limitations and optimal, performance-driven operations aligned with Lean principles for the design of future systems.

As we demonstrated in Chapter II, Lean and I5.0 are converging in significant ways. Our methodology aims to align Lean requirements with the I5.0 context from the requirements specification phase. This alignment ensures that requirements adhere to I5.0 principles, and guides subsequent engineering design phases to convert these requirements into concrete functionalities. The aim is to integrate Lean tools in a way that respects the principles of I5.0, including sustainability, resilience and human-centricity.

Integrating multiple Lean requirements in an I5.0 context, with the aim of targeting several criteria and domains during the design phases, is an appropriate solution to enhance the overall performance of the system. This early, proactive integration prevents defects and waste from occurring in the utilization/exploitation phase, reduces the risk of performance decreases and improves the efficiency of the entire production cycle from the specifications phase, thus minimizing Lean interventions in future systems and ensure that the system is aligned with the emerging principles of I5.0. Considering these requirements early in the design phase guide the integration of various technologies from the beginning, ensuring that Lean and I5.0 factors are integrated and maintained throughout subsequent design phases. This proactive approach mitigates the risks of technological advancements overlooking I5.0's critical factors, fostering a more harmonious balance between automation on one side and human integration and environmental responsibility on the other.

Many of the methods discussed in the literature lack sufficient details to address multiple Lean performance criteria, parameters and essential requirements, specifically, those who can satisfy I5.0 principles. Additionally, these methods often emphasize one phase of a system's life cycle more than others.

Design for Lean 5.0 requires the identification of specific Lean requirements for each of the identified criteria, based on their shared objectives. Since Lean concepts address the majority of criteria and domains related to I5.0 principles, we examine the connection between Lean and each domain/criteria. For example, in the "Sustainability" category, Lean-related concepts such as Lean Sustainability, Lean Green, Lean Life Cycle Assessment, and Lean Disassembly are relevant. Each "X" was analyzed in relation to its corresponding Lean concept, followed by the extraction of the relevant requirements.

Figure 19 presents our vision for introducing Lean 5.0 requirements. It encompasses the classic Lean concepts addressing I5.0 principles, along with the advanced technology aspects of I5.0 concepts.

Figure 19: Lean Requirements in an Industry 5.0 Context

Table 6 shows the extracted Lean requirements and their corresponding parameters. Each Lean requirement is represented by a single parameter and addresses an aspect of the I5.0 concept. These requirements follow the same categorization as DfX criteria categorization in Figure 12: Production, Quality, Maintenance, Sustainability, Human and Resilience. This list is not exhaustive, but it serves as a guideline for designers to incorporate the identified Lean requirements and align their system design with I5.0 considerations.

Table 6: Lean Requirements and Corresponding Parameters

DfX	Lean Requirements	Lean Parameters
Design for Production	*Lean concept: Lean Production System/ Lean Manufacturing*	
	-Small lot size -Uniform work load -Visual factory -Cellular layout (Jasti and Kodali 2015)	-Average number of units per lot -Operator idle time -Number of visual aids implemented -Cycle time within the cell
	-Reduce internal setup time -Minimizing the number of transfer operations -Eliminate temporary storage -Reducing variety of parts -Eliminating inspection -Synchronizing activities -Flexible work assignment (Houshmand and Jamshidnezhad 2006)	-Number of internal operations -Number of transfer operations -Amount of temporary storage -Part variety index -Number of inspections -Degree of alignment between related activities -Number of operators cross-trained for multiple tasks or workstations
	-Assure the free flow -Seek for a hybrid and flexible layout -Reduce traffic of materials and people -Allow the incorporation of additional modules -Able to absorb needs of layout changes (Barbosa et al. 2014)	-Waiting time -Changeover time -Handling time -Scalability index -Reconfiguration time
	-Process simplification -Identification and elimination of non-value-adding tasks -Establish control of the manufacturing process -Reduce variability -Production leveling and smoothing -Standardized work (Browning and Heath 2009)	-Number of process tasks -Percentage of non-added-value time -Number of control tasks -Number of adjustment tasks -Workload per operator/per day -Number of standard tasks
	Lean concept: Lean Assembly	
	-Reduce number of components -Use standard components -Use standard manufacturing processes (MP) -Use materials compatible with the production process -Avoid complex geometries -Avoid secondary processes -Use modular architecture -Simplify assembly -Minimize number of assembly axes (Possamai and Ceryno 2008)	-Total number of components per product -Percentage of standard components -Percentage of standard MP -Percentage of compatibility -Complexity index of component geometries -Number of secondary processes required -Modularity index -Assembly complexity index -Number of assembly axes
	-Availability of components or materials for assembly at the right time -Identify the required number of assembly operators -The use of assembly cells instead of assembly lines -U-shape assembly lines and material handling systems -Minimize Work-In-Progress stock (WIP) (Miqueo et al. 2020)	-Quantity of components or materials -Number of assembly operators -Time of assemblage operation -Assembly component handling time -WIP Visibility Index
	-Use the tools' labels, materials and instrumentation -Workplace ergonomics -Arrangement of the machines in the order of the process -One piece flow (Kowalski et al. 2020)	-Tool organization degree -Ergonomic risk index -Flow distance or time between sequential operations or workstations -Overall cycle time
Design for Quality	*Lean concept: Lean Six Sigma*	
	-Guarantee the production of the required units in the specified quantities and within the designated timeframe -Establishment of a robust and dependable manufacturing system -Facilitate immediate error detection upon its occurrence (Rahardjo et al. 2024)	-Production Capacity -Percentage of units produced without defects on the first attempt -Error detection speed

Design for Maintenance	*Lean concept: Lean Maintenance*	
	-Identify and evaluate potential failure modes of a system -Autonomous or independent maintenance -Collect equipment performance and reliability data (Mostafa et al. 2015)	-Risk Priority Number (RPN) -Percentage of maintenance tasks performed by operators independently/ frequency of autonomous maintenance activities -Percentage of required data collected
	-Availability of standard tools and instruments for regular maintenance -Availability of similar materials and spare parts -Availability of skilled workers -Minimize waste in the maintenance budgets -Feedback systems -Recording systems (De Silva et al. 2012)	-Tool availability rate -Spare parts inventory accuracy -Percentage of maintenance tasks that can be performed by the available workforce -Maintenance Cost -Feedback response rate -Data recording accuracy
	-Evaluate the Failure Rate of Component -Manage the resources necessary to rectify the failure -Identify potential failure (Kolanjiappan 2015)	-Mean Time Between Failures (MTBF) -Mean time to repair (MTTR) -Failure accuracy detection
Design for Sustainability	*Lean concept: Lean Sustainability*	
	-Visualize and understand the flow of material and information -Visualize Value added and Non value added in the production line -Reduction of resource usage and energy consumption -Use of usable waste generated during production, of the whole product or of its components after the end of its life cycle -Collect the end-of-life products, sorting, recovering useable products or components from released products for post-use -Conversion of waste into useable material after post-use cycle (Maqbool et al. 2019)	-Material and information Flow visualization index -Value-added ratio -Resource and energy use rate -Waste utilization rate -End-of-life product recovery rate -Post-use waste conversion rate
	Lean concept: Lean Green	
	-Minimize the environmental impact of companies while simultaneously lowering their manufacturing costs -Diagnostic of the wastes in the manufacturing process -Decrease the number of products that must be scrapped -Reduce the energy, raw materials, and waste involved in repairing defective products that can be transferred or passed on -Minimize energy consumption, scrap, and environmental emissions (Silva et al. 2019)	-Environmental impact index -Waste identification accuracy -Scrap rate -Consumption rate of repair resources -Emission rates
	Lean concept: Lean Re-manufacturing	
	-Material compatibility with recycling, remanufacturing, or reuse processes -Disassembly plan for each returned product -Inspection of parts disassembled into individual components -Repair or replace defective and worn-out parts by new ones and then finally reassembled as a remanufactured product (Vasanthakumar el al. 2016)	-Material compatibility rate -Disassembly time -Component inspection accuracy -Remanufacturing process rate
	Lean concept: Lean Life Cycle Assessment	
	-Reduce consumption usage such as electricity, materials and labor availability -Identify and quantify energy and materials consumed and wastes released to the environment -Eliminate the use of high-emission materials (Cheung et al. 2017)	-Consumption rate -Resource and waste tracking accuracy -Green material usage rate
	Lean concept: Lean Disassembly	
	-Disassembly of reused or remanufactured parts -Minimize changing working zones and displacements (Dayi et al. 2016)	-Disassembled part ratio -Number of work zone changes per task

Design for Humans	*Lean concept: Human-Centered Lean*	
	-Higher competency and problem solving -Improve the user safety -Mental and physical wellbeing (Hines 2022)	-Competency and problem-solving index -User safety index (Coulibaly et al. 2008) -Wellbeing index
	Lean concept: Human centered Lean automation	
	-Adding the human element in the automation system -Improve the humans' capacities to undertake physical work -Perform repetitive tasks by using human-robot collaboration -Use the real-virtual interaction -Notifies the operator by providing relevant work-related information and alerts (Malik and Bilberg 2019) -Collaboration between human intelligence and machines -Provide real-time information about the working conditions -Connect people, data, processes, and things -Integrate communication equipment -Improve the transparency of material and process movement -Leave work-intensive operations to the Cobots (Rahardjo and Wang 2022)	-Human integration rate -Skill index -Human-robot collaboration rate -Human interaction rate -Communication rate -Human-machine collaboration index -Real-time information availability -Connectivity index -Communication equipment integration rate -Real-time tracking -Cobots utilization rate
	Lean concept: Lean Safety	
	-Enhance the visibility of safety measures through clear and prominent visual indicators -Allows workers to evaluate if they are performing tasks correctly and safely -Ensure the work area and equipment are thoroughly cleaned -Interaction of workers autonomously in their workplace -Reduce the time wasted in searching materials (Sá et al. 2021)	-Safety visibility index -Activity correctness and safety -Work area cleanliness score -Autonomous interaction rate -Material search time
Design for Resilience	*Lean concept: Lean Resilience*	
	-Building redundant functions with a flexible use -Reconfigurable supply chain -Risk mitigation inventory -Omnichannel distribution systems -Multiple sourcing, diversified logistics networks, and flexible production lines (Ivanov 2022)	-Redundant function utilization rate -Supply chain reconfigurability index -Risk mitigation inventory index -Omnichannel integration rate -Number of logistics possibilities
	Lean concept: Lean Modularity	
	-Standardize the production processes, parts and modules -Independence of components and interfaces -Select an appropriate set of module variants from the product family -Assembly of customized products based on a configuration chosen by the customer (Jensen et al. 2009)	-Standardization rate -Component and interface independence rate -Number of Module variant -Number of customized products
	Lean concept: Lean Changeability	
	-Easily understandable production technologies -Easily operated and simple convertible production means -Simple and easily understandable work steps -Means of production that do not require permanent fixing to the ground -Each workplace must be readily adaptable to the needs of workers (Klemke and Nyhuis 2009)	-Technology usability index -Convertibility index -Adjustment time -Mobility of production means -Workplace adaptability

According to our analysis, the majority of Lean requirements identified fundamentally require the integration of eight key Lean tools: Single Minute Exchange of Die (SMED), 5S, Kanban, Total Productive Maintenance (TPM), Poka-Yoke (error prevention), Just in time (JIT), Heijunka and Value Stream Mapping (VSM).

For each Lean parameter, it is crucial to determine the relevant constraints that establish the operational boundaries within which the system must function. These constraints impact decisions regarding components, process configurations, capacity planning, and layout. Lean constraints are then converted into specific design specifications. For instance, a constraint to reduce setup times can be reflected in a design requirement for quick-change tooling.

The integration of Lean requirements must be carefully adapted to the specific objectives of a design project, as each objective requires a distinct set of technologies and practices. This alignment is crucial because Lean requirements are not always one-size-fits-all solutions; their effectiveness depends on their ability to address the unique challenges and goals associated with each objective. For example, the requirements required to improve production efficiency differ significantly from those needed to improve maintenance or guarantee product quality. By gearing the integration of the specific requirements of each objective, companies can leverage the most appropriate effective tools, technologies and practices. This precise focus prevents misalignment of resources and efforts, ensuring that every aspect of the Lean integration process is strategically focused on achieving the designated objectives.

The identified Lean requirements encompass technical, process, and behavioral aspects that should be considered from the requirements specification phase. The alignment of these requirements with the technological aspects of I5.0 can be addressed in subsequent design stages. Automation technologies, such as Collaborative Robots (Cobots), can streamline production while allowing human workers to focus on value-added tasks. Smart sensors and AI can enhance quality control through real-time monitoring, and predictive maintenance enabled by IoT devices helps reduce downtime. Sustainability can be achieved through green technologies and sustainable materials, while resilience is supported by AI-driven systems that adapt to changing demands. Additionally, human-centric technologies like exoskeletons and virtual training tools empower workers, creating a collaborative and efficient work environment. Further investigation into the I5.0 technologies corresponding to each Lean requirement and their integration from the design phase will be the focus of our Lean 5.0 Axiomatic model in the next section.

3. Phase 2: Axiomatic Model for Lean 5.0 Manufacturing Systems Design

The development of the Lean 5.0 Axiomatic model begins with analyzing the limitations of Lean tool applications and extracting the corresponding functional requirements to be integrated from the design phase, aiming to avoid or minimize the need for these tools in future systems. Then, each of these requirements is combined with I5.0 principles and decomposed within the context of three main facets: “Design a Sustainable Lean Manufacturing System”, “Design a Resilient Lean Manufacturing System” and “Design a Human-Centric Lean Manufacturing System”. The following sections provide a detailed explanation of these steps.

3.1 Lean Tool Application Limitations and Lean Functional Requirements Formulation

To overcome the limitations and barriers of Lean tool applications in existing systems, we analyze the functionalities of each Lean tool as applied in these systems (Chapter I, Section 3.1), along with the potential problems that may arise when implementing these functionalities. We then highlight the importance of addressing these issues from the design phase by translating the value added by each Lean tool into specific requirements for system design. We concentrate on the final result; Rather than simply identifying the tool, we need to focus on defining the desired outcome that didn't need the application of such a Lean tool.

Among the various Lean tools, we select eight tools for analysis, based on the results presented in Table 6, which are among the most widely recognized in the literature: SMED, 5S, Kanban, TPM, Poka-Yoke, JIT, Heijunka and VSM. Table 7 illustrates their application limitations in existing systems and their Functional Requirements (FRs) to be integrated from the design phase and its contributions.

Table 7: Limitations of Lean Tool Application and Lean FRs Formulation

Application limitations	Lean FRs
SMED	
-Equipment Limitations: Older equipment may not be designed for rapid changeover, requiring modifications or major investment in newer technologies. -Process Complexity: Complex tooling difficult to access or remove. -Initial Setup Time: Time needed to initially separate internal and external setup tasks. -Cultural Resistance: Operators and managers may resist changing established procedures. -Dependence on skilled operators: SMED improvements often rely heavily on trained operators to make rapid changes, introducing performance variability based on skill levels. If the design requires excessive manual adjustments, human error and inconsistency are probable. -Limited Resources: Allocating time and resources for SMED training and implementation can be challenging, especially in high-volume production environments.	**Design for Rapid Changeover** Integrating SMED into the design phase of manufacturing systems aims to design a system without or with minimum internal tasks from the beginning. We avoid the need to apply all SMED functions to an existing system. As a result, the system is designed from the beginning with minimum downtime, maximum equipment efficiency. and adaptable templates and tool holders. This can facilitate faster and easier changeovers, reducing the reliance on specialized tools and extensive training. A SMED-designed system can adapt more quickly to production changes, new product introductions, and varying customer demands. This Lean FR aims to design systems that use standardized parts, tools and processes for different products and to create standardized workstations, with easily accessible tools and materials to minimize the need for operator intervention. When everything is uniform, changeovers are naturally quicker, as the adjustments required between series are minimal.
5S	
-In existing systems, numerous tools are often necessary to keep the system functioning effectively. For this reason, 5S is often implemented reactively to remedy disorganized and cluttered workspaces. This indicates that organization was not a priority during the design phase, resulting in wasted time searching for tools, materials or information. -Superficial implementation: Organizations may prioritize initial sorting and cleaning activities for rapid visual improvement, neglecting the importance of standardization and discipline. -Major efforts to redesign workspaces and train employees in new procedures -Employees may resist changes to their routines and habits. -Time-consuming: the initial sorting and organization phase can be time-consuming and disrupt production. -Lack of real-time visual management: In many systems, 5S improvements rely on manual labelling, visual cues and signage. If these elements are not integrated into the system's design, implementing 5S will be required throughout the system's lifespan, leading to higher operating costs.	**Design for Minimal Tool Use** The aim is to design a system that minimizes the number of tools required, or that integrates the tools directly into the equipment. Integrating 5S from the design phase of the manufacturing system avoids the extra effort required to reorganize the workplace each time, avoids the risk to employee safety if tools are not placed correctly, avoids additional employee movements each time to replace tools in their place and reduces the time spent searching for tools. By integrating features such as visual management systems, standardized workflows and modular layouts directly into the design phase, we can create an environment that promotes cleanliness and order without additional intervention. Another advantage is the elimination of the need for tool carts next to machines, which not only frees up space and improves accessibility but also reduces costs associated with maintaining these carts. By designing machines that either do not require tools or provide secure storage for the few necessary tools, we can further enhance operational efficiency and streamline the workflow.

Kanban	
-Unclear Workflows: Unidentified or inconsistent workflows make it difficult to define stages on the Kanban board and track progress effectively. -Overloaded Boards: Too many tasks on the board can create information overload and make it difficult to track progress and identify priorities -Cultural Resistance: Resistance to change from employees accustomed to traditional tracking methods. -Lack of Real-Time Data: Inadequate real-time tracking tools can result in outdated information. -Complexity and Scalability: Existing systems might struggle with the complexity of tracking multiple product lines or large volumes. Scalability issues can lead to inefficiencies and loss of traceability in high-mix, high-volume environments.	**Design for Tracking** Integrating Kanban from the design phase of manufacturing systems enables a system to be designed with flow, pull production and waste reduction in mind, resulting in leaner operations and processes that become specifically designed to work with Kanban signals, ensuring the system remains dynamic and responsive to changes in production needs (as reconfigurable system). This proactive approach simplifies the initial implementation of Kanban principles and ensures their sustained application, providing long-term benefits to the manufacturing system. For example, designing a system with sensors to capture information about different product kanbans, including their locations and pathways. As far as employees are concerned, they don't need to adapt to a new system, because Kanban is the basis of their work from day one.
TPM	
-Reactive Maintenance Focus: Traditional maintenance focuses on reacting to breakdowns rather than proactively preventing them. -Cultural Resistance: Employees may resist taking on maintenance responsibilities traditionally held by specialized maintenance staff. -Equipment Design: Existing equipment might not be designed for easy maintenance.	**Design for Easy Maintenance** The integration of TPM from the design phase of manufacturing systems enables predictive maintenance programs to be established based on the condition of the equipment, rather than on arbitrary intervals. This aims to minimize downtime and extend equipment life, thereby reducing maintenance costs and improving reliability. Early consideration of correlations between key performance indicators and operational parameters helps identify the root causes of failures, enabling targeted solutions. From the beginning, equipment must be designed with ease of maintenance in mind. This includes creating machines that are easy to access for cleaning, inspection and repair, without the need for specialized tools or skills. Modular designs that allow rapid replacement of standardized parts and components can reduce the need for major maintenance efforts in the future (Coulibaly et al. 2008).
Poka-Yoke	
-Reactive error prevention: Poka-Yoke is often applied reactively to correct recurring errors or faults. This indicates that the initial design of the system or process did not prioritize error prevention, resulting in frequent problems that now need to be corrected. -Retrofitting Complexity: Existing designs may not easily accommodate mistake-proofing devices, leading to suboptimal implementations. -Cost of Implementation: Modify existing systems to implement Poka-Yoke devices can involve upfront costs for design, development, and installation. -Maintenance: Poka-Yoke devices need to be regularly maintained and adjusted to remain effective over time.	**Design for Error Prevention** Integrating Poka-Yoke from the design phase of manufacturing systems enables the prioritization of prevention over detection: while defect detection is essential, the priority is to eliminate the risk factors of error that can cause a defect. This prevention leads to give priority to low-cost, low-tech solutions: Simple, low-cost poka-yoke devices (e.g. physical barriers, color codes, jigs or checklists) are more effective and easier to implement than complex, technology-based solutions. Equipment, tools and workstations must be designed with the user in mind, so that it's easy to use them correctly. Good ergonomic design reduces the risk of errors, minimizing the need for Poka-Yoke solutions in the future.
JIT	
-In older systems, bottlenecks at any stage of production can disrupt the flow, leading to delays that impact on the whole process, making it difficult to maintain a JIT system. -Production Flexibility: Existing production processes may lack flexibility to adjust to JIT requirements, such as frequent changeovers or demand fluctuations.	**Design for Pull production** Integrating JIT from the design phase of manufacturing systems enables designing processes around pull signals, leading to smoother flow and fewer potential bottlenecks. By designing cellular layout and workstations to be flexible and modular, allowing quick reconfiguration to accommodate different products and processes, materials become available

-Inflexible Layouts: Existing production schemes may be rigid and not suited to the changing nature demanded by JIT. -Long Travel Distances: Poorly designed layouts with long travel distances between workstations increase material handling time	when needed, minimizing waiting times and work-in-progress levels.
Heijunka	
-Variability in Demand: It can be difficult to level production when demand varies significantly, leading to underutilization or overburdening of resources. -Complexity of Product Mix: Existing systems may have a wide variety of products with different processing times and resource requirements. -Long Lead Times and Setup Times: Long lead times and time-consuming changeovers make it difficult to achieve a level production flow in existing systems.	**Design For Leveling** Integrating Heijunka from the design phase can reduce the need for extensive overhauls in the future by focusing on Standardization and modularity to enhance flexibility and responsiveness to fluctuating demand while supporting Heijunka principles and using Technology enables real-time monitoring of production levels, facilitates decision-making, and optimizes resource utilization. Integrating mass customization can reduce the need for the Heijunka tool by creating flexible and adaptable systems that accommodate varying customer demands and achieve efficient production without leveling production schedules. In this context, modular designs that allow for quick reconfiguration, advanced automation technologies to handle customized components, and a robust data management system for facilitating real-time decision-making based on customer feedback can be integrated from the design phase.
VSM	
-Complex and Disorganized Layouts: Existing layouts may be complex and disorganized, making it challenging to map the value stream accurately. -Inaccurate data collection: VSM relies heavily on accurate data concerning cycle times, lead times and inventory levels. In existing systems, the absence of reliable data collection processes can lead to inaccurate value stream maps, resulting in misguided improvement efforts.	**Design for Flow Visualization** Integrating VSM from the design phase of manufacturing systems enables NVA to be identified and eliminated at an early stage, avoiding rework at a later stage in the process, thus saving time and resources. One of the main objectives is to automate repetitive tasks and free up human resources for value-added activities. Early identification of metrics in the design phase enables the company to position itself in relation to the optimal process designed at the beginning, by comparing the real value of these metrics during the manufacturing phase with the optimal process designed at the beginning.

To integrate the identified Lean FRs in alignment with I5.0 principles, we present our generalized Axiomatic model in the following section, which offers a flexible framework that can be adapted to various system designs.

3.2 Determination of the Highest-Level FR of the Lean 5.0 Axiomatic Model and its Decomposition

In this section, we propose a generalized Axiomatic model for Lean 5.0 Manufacturing Systems Design, consisting of generalized Lean Functional Requirements (FRs), Design Parameters (DPs) and Process Variables (PVs), which can be applied and adapted to different system designs. It serves as a guide for designers to integrate Lean requirements early in the design phase within an I5.0 context.

Following the AD method, the first step in the design process is to define the highest-level FR in the functional domain. At this stage many FRs may be established. Each FR established at this stage may lead to a completely different manufacturing system design. In this work the following has been selected as the highest FR.

FR0= Provide a Waste-Free, Human-Centric and Autonomous Production Environment

The second step consists of selecting the DPs, through a mapping process between the functional domain and the physical domain which satisfy the FRs established in the previous step. Addressing FRs with the right set of DPs is as critical as selecting the right FRs for the design process. The following DP is selected to satisfy the highest-level FR.

DP0= Design a Lean 5.0 System

The third step consist of selecting the PVs. The DPs in question are achieved by proper selection of PVs in the process domain. According to (Houshmand and Jamshidnezhad 2006), PVs has an important role to better understand the design outputs. The relationship between DPs and PVs is analogous to that between FRs and DPs.

PV0= Adapt Lean Functionalities to Industry 5.0 Principles

FR0 consists of three fundamental facets of Lean in the context of I5.0: "Sustainable Lean Manufacturing System", Resilient Lean Manufacturing System" and "Human-Centric Lean Manufacturing System".

As shown in Figure 20, FR0 is decomposed into FR1, FR2 and FR3. FR1 is defined as "Design a Sustainable Lean Manufacturing System", it could be done by a sustainable focus on the elimination of all forms of waste that may arise in the manufacturing process. This can be made by decreasing the number of system components that must be scrapped and eliminate the resulting raw materials, energy and waste associated (Silva et al. 2019). Considering this FR from the early design phases can decrease the amount of energy, raw material and waste that is used or generated in the manufacturing phase and reduce the environmental impacts of companies while reducing their manufacturing costs. The DP that satisfies FR1 could be DP1 "Minimize Environmental Impact", which could be concerning the selection of eco-friendly components that are renewable, recyclable, or biodegradable and prioritize materials with lower carbon footprints and minimal toxicity. The corresponding PV1 could be "Waste Elimination and Recycling" which means applying an operating process to minimize waste production and ensure proper treatment of unavoidable waste.

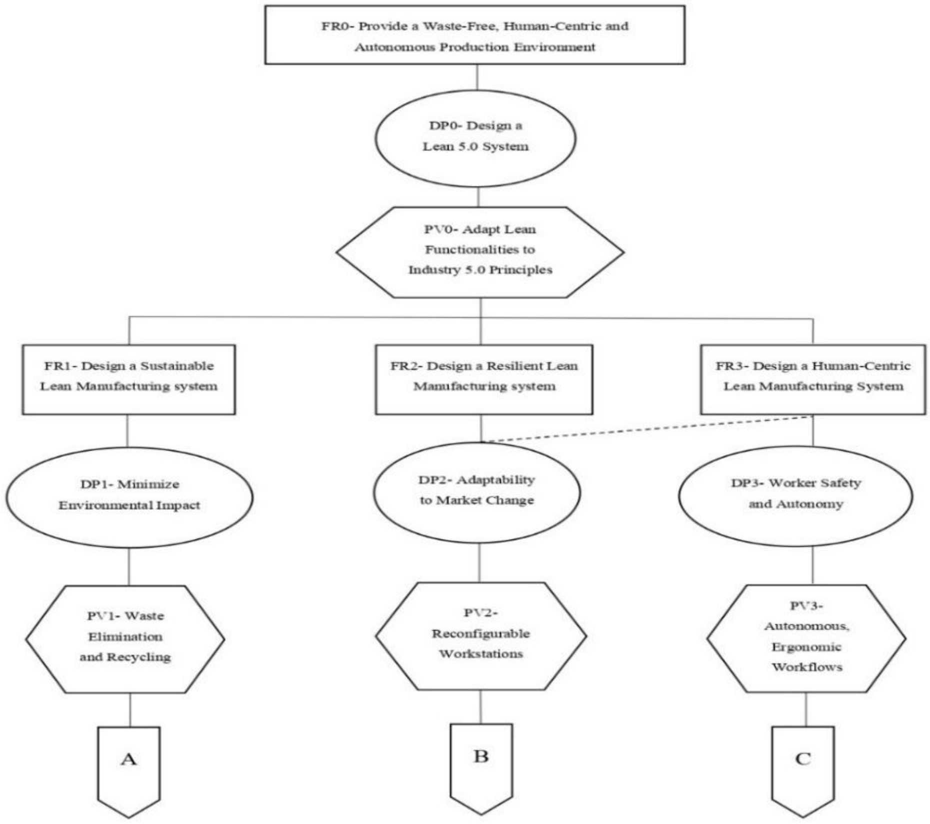

Figure 20: First Level of the Lean 5.0 Manufacturing System Decomposition

Regarding FR2, while Lean practices aim to minimize all potential waste in the process, resilient practices seek to minimize the impact of any unexpected event or crisis on the organization and the process, in order to return them to their original state before the disruption occurs. According to (Ivanov 2022), one of the main idea of Lean resilience is manufacturing systems less sensitive to external uncertainty by favorizing internal flexibility and reconfigurability. FR2 defined as "Design a Resilient Lean Manufacturing System" could be done by designing a reconfigurable manufacturing system that adapt quickly to market change. The DP that satisfies FR2 could be DP2 "Adaptability to Market Change". The corresponding PV2 could be "Reconfigurable Workstations", which means designing workstations or production lines with flexible layouts that can be easily reconfigured for different product types or production needs.

FR3 defined as "Design a Human-centric Lean Manufacturing System'' could be done by adding the human element in the automation system where employees are responsible for planning, material flow and some inspection tasks. Operators are also able to perform mental tasks such as reasoning, decision and perception (Malik and Bilberg 2019). One of the main factors in Lean Human-centricity is employee safety. According to (Sá et al. 2021), Lean safety consists of creating a safe work environment and enables workers to assess whether or not they are performing their activities correctly. So, DP3 could be "Worker Safety and Autonomy" and PV3 could be "Autonomous, Ergonomic Workflows", it means design workflows that allow operators a degree of autonomy in decision-making and task execution, and integrate ergonomic principles into workstation design, tool selection and work procedures to minimize physical strain and discomfort.

Independence axiom (IA) requires a Design Matrix (DM) to be uncoupled or at least decoupled. The decoupled DM of the proposed FRs and DPs is shown in the equation (1) which represents an acceptable design such as the matrix is triangular. Aside from the coupling to FR2, DP2 has a relationship to FR3 since the design of Human-centric system can improve the human resilience which is directly related to adapt the change of the market.

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} X & & \\ & X & \\ & X & X \end{bmatrix} * \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix} \quad (1)$$

The decomposing process continues until the proposed DPs are fully understood to implement. The 3 branches A, B and C in Figure 20 are detailed in sections 3.3, 3.4 and 3.5. Table 8 summarizes the developed Axiomatic model for Lean 5.0 Manufacturing System, which will be detailed in the following sections.

Table 8: Summary of the Lean 5.0 Manufacturing System Axiomatic Model

Lean 5.0 Functional Requirements	Design Parameters	Process Variables
FR1: Design a Sustainable Lean Manufacturing system	DP1: Minimize Environmental Impact	PV1: Waste Elimination and Recycling
FR2: Design a Resilient Lean Manufacturing system	DP2: Adaptability to Market Change	PV2: Reconfigurable Workstations
FR3: Design a Human-Centric Lean Manufacturing System	DP3: Worker Safety and Autonomy	PV3: Autonomous, Ergonomic Workflows
FR11: Design for Sustainable Pull Production	DP11: Minimize Raw Materials and Process Time	PV11: AM technologies
FR12: Design for Sustainable Leveling	DP12: Short-term adjustments	PV12: Automated planning
FR13: Design for Sustainable Tracking	DP13: Automatic identification and transportation of materials	PV13: Monitoring and localization of materials
FR14: Design for Sustainable Flow Visualization	DP14: Collect and visualize environmental information	PV14: Real-Time data collection
FR15: Design for Sustainable Rapid Changeover	DP15: External Changeover	PV15: Quick-Change Fixtures and Mechanisms
FR16: Design for Sustainable Minimal Tool Use	DP16: Tool Removal or Standardization	PV16: Multi-Functional Tools
FR17: Design for Sustainable Easy Maintenance	DP17: Customizable Alerts	PV17: Visual Management and Metrics
FR18: Design for Sustainable Error Prevention	DP18: Automatic Error Detection	PV18: Error-Proofing Devices and Mechanisms
FR21: Design for Resilient Pull Production	DP21: Machine-Machine Interaction	PV21: Adaptive Inventory Systems
FR22: Design for Resilient Leveling	DP22: Predict Process Behavior	PV22: Real-Time Data and Monitoring Systems
FR23: Design for Resilient Tracking	DP23: Predict Demand and Adjust Kanban Workflows	PV23: Implement AI and Machine Learning Algorithms
FR24: Design for Resilient Flow Visualization	DP24: Multiple Simulations Mapping	PV24: Virtual Simulation techniques

FR25: Design for Resilient Rapid Changeover	DP25: Modular Equipment Design	PV25: Additive Manufacturing
FR26: Design for Resilient Minimal Tool Use	DP26: Tool Availability	PV26: Built-In Tool Functions
FR27: Design for Resilient Easy Maintenance	DP27: Automated Monitoring and Diagnostics	PV27: Predictive Maintenance Algorithms
FR28: Design for Resilient Error Prevention	DP28: Prediction Based On Past Data	PV28: AI Algorithms
FR31: Design for Human-Centric Pull Production	DP31: Human-Robot Collaboration	PV31: Task Classification for Humans and Machines
FR32: Design for Human-Centric Leveling	DP32: Reduce Effort For Levelling	PV32: Real-Time Monitoring
FR33: Design for Human-Centric Tracking	DP33: Workload Information Feedback	PV33: Digital Kanban Boards
FR34: Design for Human-Centric Flow Visualization	DP34: Workers Training	PV34: VSM Simulations
FR35: Design for Human-Centric Rapid Changeover	DP35: Digital Work Instructions	PV35: Augmented Reality Guides
FR36: Design for Human-Centric Minimal Tool Use	DP36: Identification and the localization of objects	PV36: Virtual Tool Placement Guide
FR37: Design for Human-Centric Easy Maintenance	DP37: Operators and Maintenance Specialists Interaction	PV37: Reality and virtual Simulation
FR38 Design for Human-Centric Error Prevention	DP38: Provide Operators With Real-Time Feedback and Guidance	PV38: AR Guidance for Operators

3.3 Decomposition of FR1 "Design a Sustainable Lean Manufacturing System"

Figure 21 shows the decomposition of FR1 "Design a Sustainable Lean Manufacturing System".

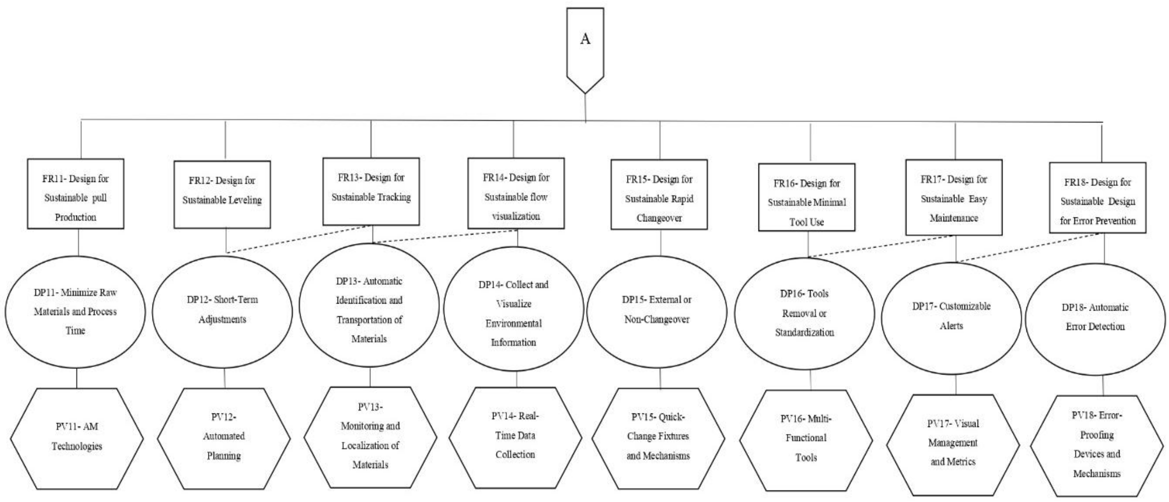

Figure 21: Decomposition of FR1 "Design a Sustainable Lean Manufacturing System"

FR11 “Design for Sustainable Pull Production” corresponding to JIT Lean Tool, concerns the identification of potential sources of waste in future manufacturing processes (such as in inventory, workflows, queues, etc.) and develop targeted action plans to eliminate them. To integrate JIT considerations into system design, a focus on the flow shop production type could be essential, as it allows for better planning when product families are predefined and known within the system. In a flow shop, processes could be streamlined to minimize environmental impacts while still benefiting from JIT principles. This contrasts with job shop environments, where varied products and production paths make it challenging to fully implement JIT and control emissions as efficiently. According to (Valamede and Akkari 2020), the exact personal customer request can be prepared by Additive Manufacturing (AM) technologies, using less raw materials and process time. The DP that satisfies FR11 could be DP11 “Minimize Raw Materials and Process Time” and PV11 could be “AM Technologies”. AM can often produce complex assemblies as a single piece, eliminating the need for multiple components and the associated assembly processes. This reduces the total number of steps in the manufacturing process, saving time, cost and energy.

FR12 “Design for Sustainable Leveling” corresponding to Heijunka Lean Tool, concerns the integration of Internet of Things (IoT) and Big Data Analytics to enable small inventory buffer and reduce the irregularity (mura) and overburden (muri) (Kjellsen et al. 2021). The concept of leveling include the automation of the planning to smoothly integrated short-term adjustments (Naciri et al. 2022). DP12 could be “Short-Term Adjustments” and PV12 could be “Automated Planning”, this can be made by equipping the manufacturing system with IoT sensors to collect real-time data in the future system designed on machine performance, material flow, and product status. This data is crucial for automated planning and monitoring production levels.

FR13 “Design for Sustainable Tracking” corresponding to Kanban Lean Tool (in the context of a job shop), concerns the force towards recycling culture and improve resources utilization to focus on material optimization and energy conservation and leads to a pollution free environment (Kumar and Mathiyazhagan 2020). It consists as well on virtual real-time representation of physical objects and continuous monitoring of work in progress (Mayr et al. 2018). DP13 could be “Automatic Identification and Transportation of Materials” and PV13 could be “Monitoring and Localization of Materials”. It may concerns integrating suitable technologies for automatic identification, such as RFID (Radio-Frequency Identification). Implement RFID tags for real-time tracking of materials as they move through the manufacturing process.

FR14 “Design for Sustainable Flow Visualization” corresponding to VSM Lean Tool, provide real-time KPIs and immediate feedback on decisions, and eliminate inventory errors through real-time exact inventory tracking (Wang et al. 2024). The focus on sustainability can be ensured by designing embedded sensors in the system to collect complete and proper environmental information (Rahardjo and Wang 2022). DP14 could be “Collect and Visualize Environmental Information” and PV14 could be “Real-Time Data Collection”.

FR15 “Design for Sustainable Rapid Changeover” corresponding to SMED Lean Tool, concerns manufacturing variable work-pieces with the least amount of setup time (Mayr et al. 2018). It can contains the use additive manufacturing to produce varying workpieces with minimum setup time and omit times for selection, search tools, and work-pieces adjustment (Rahardjo et al. 2023). DP15 could be “External or Non-Changeover”, it concerns the design of an equipment with maximum external operations that didn’t require production stoppage. This takes into consideration the design workstations without or with easy access to changeover points. PV15 could be “Quick-Change Fixtures and Mechanisms”, it concerns the Integration quick-release mechanisms and tools into equipment design.

FR16 “Design for Sustainable Minimal Tool Use” corresponding to 5S Lean Tool, concerns the reduce the workplace organization time. During the design phase, a thorough assessment can be conducted to identify essential tools, machines, and processes, allowing for the elimination of non-essential elements and resulting in reduced organization and handling time. DP16 could be “Tools Removal or Standardization”, it involves eliminating the need for tools whenever possible and standardizing all tools used in the process regarding specifications, dimensions, and performance. PV16 could be “Multi-Functional Tools”, which means considering the tools that serve multiple purposes, reducing the number of individual tools needed.

FR17 “Design for Sustainable Easy Maintenance” corresponding to TPM Lean Tool, concerns the self-diagnose and report the status of each machine or equipment to the appropriate operational control center via the Internet (Korchagin et al. 2022). TPM uses complex algorithms to predict defects, to increase the accuracy of life expectancy of equipment (Valamede and Akkari 2020). DP17 could be “Customizable Alerts”, it concerns the configuration of the system to generate alerts based on pre-defined risk thresholds and notify maintenance teams of potential issues before they lead to machine failure, allowing for timely interventions. PV17 could be “Visual Management and Metrics”, it concerns providing real-time insights into the status of each machine, including operational efficiency, energy consumption, and maintenance needs.

FR17 “Design for Sustainable Easy Maintenance” and DP16 “Tool Removal or Standardization” appear to be closely related. Any changes made to the design for maintenance typically impact the design aimed at minimizing tool usage.

FR18 “Design for Sustainable Error Prevention” corresponding to Poka-Yoke and ANDON Lean Tools, concerns the detection of incorrect deliveries, prevention the value of defective parts from being added and automatically respond to abnormalities (Mayr et al. 2018). It consist of integrating Smart Poka-Yoke devices, in turn, work with real-time data from production flow, which is effective in reducing waste, as well as preventing the issues spread to next workstations (Valamede and Akkari 2020). DP18 could be “Automatic Error Detection” and PV18 could be “Error-Proofing Devices and Mechanisms”, it consist of designing systems with error proofing solutions in such a way that human errors are minimized or eliminated, and integrating IoT sensors and smart devices to automatically detect errors if they occur.

Equation 2 represents a decoupled design of the design; thus, our Sustainable Lean Manufacturing System design is acceptable.

$$\begin{bmatrix} FR11 \\ FR12 \\ FR13 \\ FR14 \\ FR15 \\ FR16 \\ FR17 \\ FR18 \end{bmatrix} = \begin{bmatrix} X & & & & & & & \\ & X & & & & & & \\ & X & X & & & & & \\ & & X & X & & & & \\ & & & & X & & & \\ & & & & & X & & \\ & & & & & X & X & \\ & & & & & & X & X \end{bmatrix} * \begin{bmatrix} DP11 \\ DP12 \\ DP13 \\ DP14 \\ DP15 \\ DP16 \\ DP17 \\ DP18 \end{bmatrix} \quad (2)$$

3.4 Decomposition of FR2 "Design a Resilient Lean Manufacturing System"

The analysis and decomposition of FR2, "Design a Resilient Lean Manufacturing System", is conducted using the same approach as that for FR1, as illustrated in Figure 22.

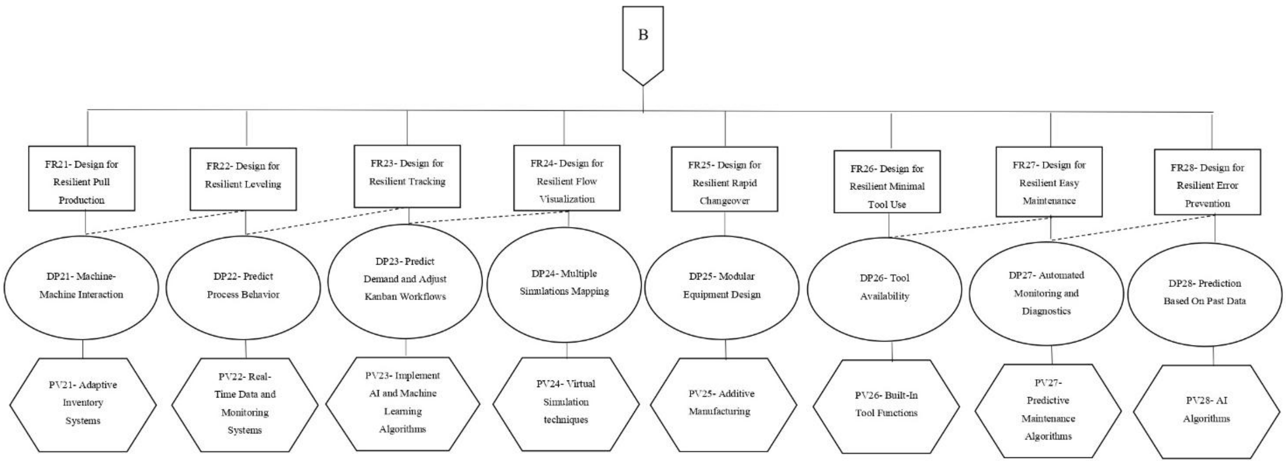

Figure 22: Decomposition of FR2 "Design a Resilient Lean Manufacturing System"

FR21 "Design for Resilient Pull Production" concerns keeping the production flows always pulled and tracked in real-time without generating excessive production and integrate machine-to-machine to assist in real-time control stability (Rossi et al. 2022). DP21 could be "Machine-Machine Interaction" and PV21 could be "Adaptive Inventory Systems", it concerns designing systems with capabilities for real-time data collection from various sources using AI and machine learning, to create adaptive inventory systems that can automatically adjust inventory levels based on real-time demand data and predictive analysis.

FR22 "Design for Resilient Leveling" concerns using sensors and vision technology to collect and connect data from various sources, to predict process behavior, and increase production process reliability (Kjellsen et al. 2021). The corresponding DP22 could be "Predict Process Behavior" and PV22 could be "Real-Time Data and Monitoring Systems", which concerns integrating real-time data collection and monitoring systems from the design to provide visibility into production and demand, minimizes variability, reduces the risk of disruptions, and ensures that manufacturing processes align closely with demand.

FR23 "Design for Resilient Tracking" concerns facilitating data and information sharing and automatically ordering raw materials to build a better supply and marketing network to predict production behavior and solutions to reduce bottlenecks (Rahardjo and Wang 2022). The corresponding DP23 could be "Predict Demand and Adjust Kanban Workflows" and PV22 could be "Implement AI and Machine Learning Algorithms".

FR24 "Design for Resilient Flow Visualization" concerns the use of virtual Simulation techniques, allowing multiple mapping possibilities to be studied and interpreted by managers before they are put into practice, which contributes to decision making (Valamede and Akkari 2020). The corresponding DP24 could be "Multiple Simulations Mapping" and PV24 could be "Virtual Simulation Techniques".

FR25 "Design for Resilient Rapid Changeover" concerns the use of modular manufacturing and additive manufacturing to reduce the setup time (Jurík et al. 2020). As well, the use of digital twin to analyze the collected data and comparison of improved process (Rahardjo et al. 2023). According to (Mayr et al. 2018), additive manufacturing (AM) is expected to achieve the highest impact on setup time. Variable work-pieces may be manufactured with the least amount of setup time because AM methods are not product-specific. The corresponding DP25 could be "Modular Equipment Design", it concerns designing an equipment with modular components that can be quickly swapped, this takes into consideration the design of equipment that can perform several functions without requiring major reconfiguration. PV25 could be "Additive Manufacturing".

FR26 "Design for Resilient Minimal Tool Use" concerns combining 5S with digital tool to real-time data collection and take action quickly (Mrabti et al. 2023). The DP that satisfies FR26 could be DP26 "Tool Availability". To make sure the responsiveness to different changes that may acquire, PV26 that may ensure the regular availability could be "Built-In Tool Functions", which concerns the design of equipment with the functionalities of the necessary tools integrated into its components. This eliminates the need for separate tools and ensures that all required functionalities are readily available as part of the equipment.

FR27 "Design for Resilient Easy Maintenance" concerns use autonomous maintenance to predict future equipment failures, detect potential errors, and send maintenance instructions to the maintenance team (Rahardjo and Wang 2022). The corresponding DP27 could be "Automated Monitoring and Diagnostics", it concerns the integration of automated systems that continuously monitor equipment health and provide real-time diagnostics for proactive maintenance. PV27 could be "Predictive Maintenance Algorithms", which concerns the implementation AI-driven predictive maintenance algorithms that analyze data from sensors to predict equipment failures.

FR28 "Design for Resilient Error Prevention" concerns to ensure the adaptability and ensuring the resilience of quality control measures by integrating AI algorithms that can learn from evolving production environments, adjusting error prevention strategies accordingly (Wolniak 2024). Poka-Yoke uses machine-learning technologies to process past data and operate with the prediction of future problems in the process (Rossi et al. 2022). DP28 could be "Prediction Based on Past Data" and PV28 could be "AI Algorithms".

Equation 3 represents a decoupled design of the design; thus, our Resilient Lean Manufacturing system design is acceptable.

$$\begin{bmatrix} FR21 \\ FR22 \\ FR23 \\ FR24 \\ FR25 \\ FR26 \\ FR27 \\ FR28 \end{bmatrix} = \begin{bmatrix} X & & & & & & & \\ X & X & & & & & & \\ & X & X & & & & & \\ & & X & X & & & & \\ & & & & X & & & \\ & & & & & X & & \\ & & & & & X & X & \\ & & & & & & X & X \end{bmatrix} * \begin{bmatrix} DP21 \\ DP22 \\ DP23 \\ DP24 \\ DP25 \\ DP26 \\ DP27 \\ DP28 \end{bmatrix} \quad (3)$$

3.5 Decomposition of FR3 "Design a Human-Centric Lean Manufacturing System"

We use the same approach to decompose FR3 "Design a Human-Centric Lean Manufacturing System", as illustrated in Figure 23.

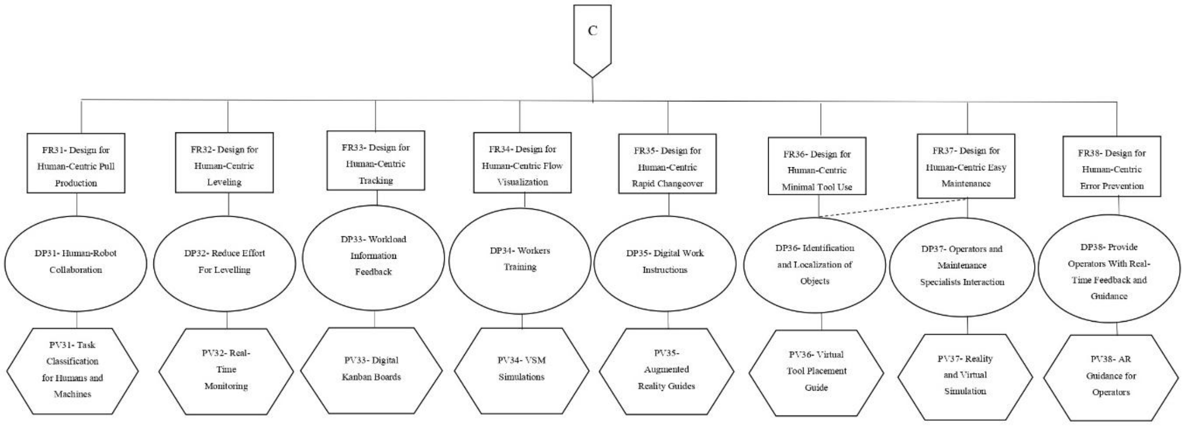

Figure 23: Decomposition of FR3 "Design a Human-Centric Lean Manufacturing System"

FR31 "Design for Human-Centric Pull Production" could involve the use of robots to deliver a product to a human operator in time to ensure continuous work (Stadnicka and Antonelli 2019). DP31 could be "Human-Robot Collaboration", it means assigning repetitive and monotonous tasks to the robots/machines and the tasks which need critical thinking to the humans. PV31 could be "Task Classification for Humans and Machines".

FR32 "Design for Human-Centric Leveling" concerns Integrate Information and Communication Technologies into production to balance loads in term of work to both operators and machines (Boutbagha and El Abbadi 2024). The corresponding DP32 could be "Reduce effort for levelling" and PV32 could be "Real-Time Monitoring". The presence of real-time monitoring systems for production processes and inventory levels helps in making quick adjustments with minimal human effort.

FR33 "Design for Human-Centric Tracking" concerns control specialists' workload, thus maintaining their work pressure within the allowable limit (Kabzhassarova et al. 2021). DP33 could be "Workload Information Feedback" and PV33 could be "Digital Kanban Boards", which means designing the system with integrated digital Kanban boards accessible from multiple devices (e.g., tablets, smartphones, desktops).

FR34 “Design for Human-Centric Flow Visualization” concerns Training workers through VSM simulations and evaluate the practicality of each map option (Rahardjo and Wang 2022). DP34 could be “Workers Training” and PV34 could be “VSM Simulations”.

FR35 “Design for Human-Centric Rapid Changeover” concerns the use virtual simulation technologies to improve workers understanding of each step of the changeover process (Rahardjo et al. 2023). DR35 could be “Digital Work Instructions”, it provide digital work instructions to assist operators in performing setups quickly and accurately. The corresponding PV35 could be “Augmented Reality guides”.

FR36 “Design for Human-Centric Minimal Tool Use” concerns the use of Auto-ID to ensures the identification and the localization of objects which reduces search time and applying AR to replace physical shadow boards, as virtual elements guide operators where to place tools (Mayr et al. 2018). DP36 could be “Identification and Localization of Objects” and PV36 could be “Virtual Tool Placement Guide”.

FR37 “Design for Human-Centric Easy Maintenance” concerns use reality and virtual simulation instruments with AR instruments to ensure the interaction of factory floor operators with maintenance specialists (Valamede and Akkari 2020). The corresponding DP37 could be “Operators and Maintenance Specialists Interaction” and PV37 could be “Reality and Virtual simulation”.

FR38 “Design for Human-Centric Error Prevention” concerns technical installations that help employees to avoid mistakes and inform them in case a mistake occurs by establishing a real-time, continuous connection between machine and human to enable the operator to focus on other tasks while staying informed of the machine's status without necessitating its permanent presence to monitor the machine (Naciri et al. 2022). To achieve this, it is necessary to send data and interpreted information to visual field of employee through AR device, help them to solve issues and take better decisions quickly (Valamede and Akkari 2020). DP38 could be “Provide Operators with Real-Time Feedback and Guidance”, it can help to prevent errors during assembly or processing. PV38 could be “AR Guidance for Operators”.

Equation 4 represents a decoupled design of the design, thus our Human-Centric Lean Manufacturing System design is acceptable.

$$\begin{bmatrix} FR31 \\ FR32 \\ FR33 \\ FR34 \\ FR35 \\ FR36 \\ FR37 \\ FR38 \end{bmatrix} = \begin{bmatrix} X & & & & & & & \\ & X & & & & & & \\ & & X & & & & & \\ & & & X & & & & \\ & & & & X & & & \\ & & & & & X & & \\ & & & & & X & X & \\ & & & & & & & X \end{bmatrix} * \begin{bmatrix} DP31 \\ DP32 \\ DP33 \\ DP34 \\ DP35 \\ DP36 \\ DP37 \\ DP38 \end{bmatrix} \quad (4)$$

Each FR-DP-PV triad represents a structured mapping that fulfills a specific objective in the system design. However, integrating multiple parameters without ensuring the independence of FRs and DPs can lead to coupling and contradictions, violating the Axiomatic principles and potentially degrading system performance.

If the Independence Axiom is respected, a DP may not directly interfere with another FR, but the interaction of multiple DPs can create emergent behaviors that lead to contradictions. Even with independent FR-DP mappings, the DPs might share common resources or constraints in the system. This can lead to contradictions:

- Example: In a manufacturing system, one FR might demand high-speed production processes (DP1) to maximize efficiency, while another FR requires precise quality control (DP2) to ensure product consistency. While these DPs independently fulfill their respective FRs, their physical integration can create contradictions, as increasing production speed may compromise quality control accuracy.

Integrating multiple DPs can lead to contradictions because real-world systems are subject to complexities and constraints that are not explicitly modeled in the AD framework. Even if FR-DP independence is maintained, the physical implementation of DPs can lead to unforeseen interactions or conflicts. For example, two independent DPs may require the use of the same resource, such as space, energy, or material, creating resource contention. Additionally, emergent properties, which are behaviors resulting from the collective interaction of multiple DPs, can produce outcomes that contradict system-level goals.

So, even if the Independence Axiom is respected, contradictions can still arise due to system-level interactions, shared physical or operational constraints, or emergent behaviors when DPs are combined. Therefore, while DPs are not required to be isolated, careful system integration and consideration of secondary effects are essential to avoid unintended contradictions. The third phase of our methodology addresses this issue by leveraging the demonstrated complementarity between AD and TRIZ to propose a structured approach for formulating and resolving potential contradictions that may arise from the integration of multiple Lean 5.0 parameters. This methodology is introduced in the following section and further detailed in Chapter IV.

4. Phase 3: Formulate and Resolve Contradictions

Despite the immense importance of integrating Lean 5.0 requirements from the design phase, their integration can sometimes lead to contradictions. It is therefore essential to resolve these contradictions during the design phase to prevent them from hindering overall system performance.

Design parameters are an essential aspect of the system design process. They encompass the key attributes and constraints that define a system's functionality, performance and usability. These parameters can include dimensions, material properties, performance specifications and user requirements. While design parameter models are often used to address specific design challenges, the generalization of these parameters can provide a broader, more flexible framework for solving a wide range of design problems.

To address the gap in resolving contradictions that may arise between various Lean 5.0 requirements, we propose a new methodology “Lean 5.0 Parameter Integration Matrix (L5.0PIM)”. L5.0PIM is based on the extraction of generalized parameters from Lean tools, while considering I5.0 principles. It aims to 1) identify the technical and physical contradictions that may arise from the integration of multiple Lean 5.0 requirements, and 2) offer guidance for their resolution using the TRIZ theory principles for addressing technical and physical contradictions. Figure 24 simplifies the global vision of the L5.0PIM. The detailed explanation of this methodology is presented in Chapter IV.

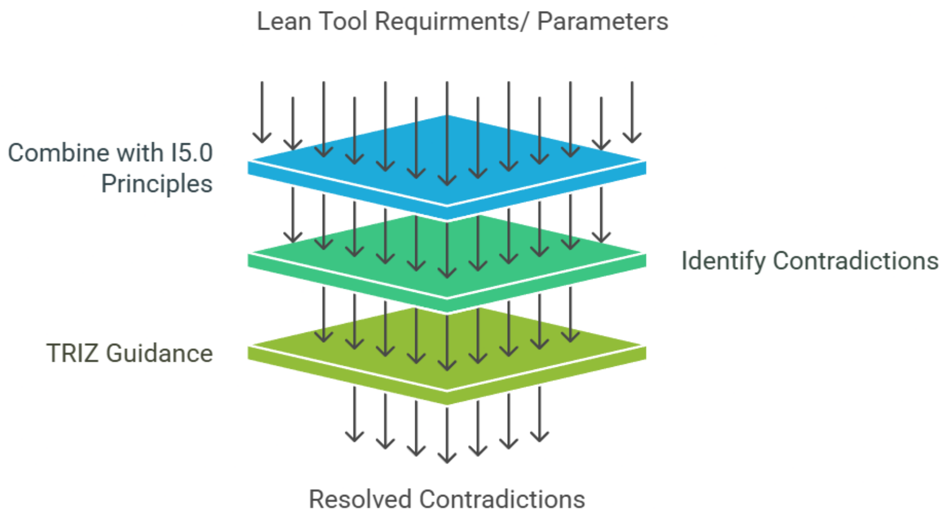

Figure 24: Global Vision of L5.0PIM

Conclusion

In this chapter, we presented the first two phases of our methodology and introduced a generalized Axiomatic model for Lean 5.0 manufacturing systems, providing a roadmap for designing high-performance intelligent systems from the initial design phase. This model emphasizes minimal reliance on Lean tools during the operational phase while aligning with I5.0 principles. Additionally, we proposed a set of over 100 Lean requirements and evaluation parameters in the context of I5.0, aimed at assessing the alignment of the designed system with Lean and I5.0 principles. Our study focuses on proposing a set of independent solutions that can be integrated during the design phase, with each solution representing a specific combination of Lean tools and I5.0 principles. These solutions are presented in a generalized manner, allowing for customization to suit various system designs. However, trying to integrate multiple parameters may cause the appearance of contradiction. In the next chapter, we proceed with the third phase of our methodology and propose our approach to address this issue.

Chapter IV: A New TRIZ-based Approach for Designing Inventive Manufacturing Systems

Introduction

Integrating Lean tool requirements from the design phase reduces the need to apply them during the use phase of future manufacturing systems and can help designers to design a manufacturing system with the desired performance. In the previous chapter, we have identified a list of Lean Functional Requirements (FRs) in an I5.0 context, their corresponding Evaluation Parameters (EPs), as well as their Action Parameters (APs) resulting from the Lean 5.0 Axiomatic model. However, trying to integrate several requirements in the design of a manufacturing system can generate contradictions.

While the first two phases of our methodology were examined in the previous chapter, this chapter is dedicated to the third phase, which focuses on formulating and resolving contradictions that may arise from the integration of Lean 5.0 requirements.

In this chapter, we propose a generalized methodology that can be adapted to different types of contradictions caused by Lean 5.0 requirements integration and to different problems and sectors. The literature review that we have conducted in chapter II between Lean and TRIZ has shown that there is a lack of research that have use TRIZ to resolve contradictions between Lean requirements itself and between multiple Lean requirements and technical requirements. For this reason, we analyze this gap and propose a new methodology based on TRIZ, aimed at simultaneously identifying and resolving the technical and physical contradictions that may arise at two levels: First, among the Lean 5.0 parameters, and second, between these parameters and other technical system parameters.

1. TRIZ Theory (Theory of Inventive Problem Solving)

TRIZ, the Russian acronym for "Teoriya Resheniya Izobreatatelskikh Zadatch" (Theory of Inventive Problem Solving), was introduced by Russian engineer and scientist Genrikh Altshuller in 1946. It is a problem-solving methodology based on logic and data rather than intuition, designed to accelerate creative problem-solving. TRIZ offers a structured, algorithmic approach that ensures repeatability, predictability, and reliability. Altshuller developed this approach after analyzing thousands of patents and identifying patterns that revealed technical system evolution is governed by objective laws. These laws can be used to guide innovation, proving that inventiveness and creativity are learnable skills, fundamentally transforming traditional views of creativity (Kumaresan and Saman 2011). In 1946, Genrikh Altshuller introduced the main concepts of TRIZ: contradiction, ideality and the evolution patterns (Al′tshuller 1999). TRIZ provides a set of technical methods and tools to search the optimal solutions to integrate some requirements and criteria, like contradictions matrix, separation principles, standard solutions, etc. Figure 25 summarizes the TRIZ approach to problem-solving.

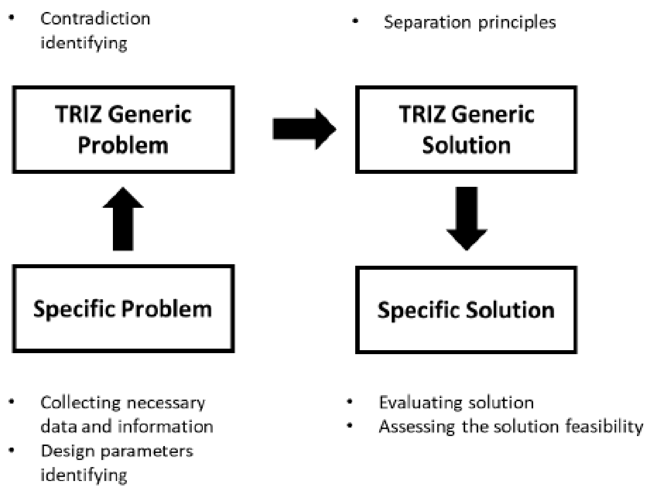

Figure 25: TRIZ Approach to Solve Problems (Navas and Machado 2013)

Contradictions in engineering systems arise when improving one feature leads to the deterioration of another. There are two main types: technical and physical contradictions. A technical contradiction (TC) arises when improving one feature of a system negatively impacts another. As an example, in the design of a car, enhancing engine power to increase speed often results in higher fuel consumption, which reduces efficiency. This creates a technical contradiction: the desire for greater performance conflicts with the need for better fuel economy. Addressing such contradictions is key to optimizing system performance without sacrificing other critical aspects.

A physical contradiction (PC) occurs when the same subsystem of a technical system is required to meet conflicting demands, such as possessing mutually exclusive properties, characteristics, or parameters. To clarify this concept, consider the example of an airplane wing: it needs to be both lightweight to improve fuel efficiency and strong enough to withstand aerodynamic forces, which presents a physical contradiction. These two types, physical and technical, are linked together in one problem model so-called system of contradictions.

As illustrated in Figure 26, the system of contradictions in TRIZ theory is based on conflicting Evaluation Parameters (EPs) and opposing values of a single design parameter when aiming for a specific desired outcome. Therefore, studies within the TRIZ framework must identify contradictory parameters or values when targeting a particular result. However, this model of contradiction typically involves two EPs and one Action Parameter (AP). In real-world problems, multiple EPs and APs may be involved in the system of contradictions. The concept of contradiction has been expanded within the framework of OTSM-TRIZ (Dubois et al. 2009). Two types of contradictions are introduced: the System Contradiction and the Parameter Contradiction, which generalize the TRIZ technical and physical contradictions, respectively. Additionally, OTSM-TRIZ proposes a System of Contradictions to establish coherence between the levels of System Contradiction and Parameter Contradiction, as highlighted in bold in Figure 26. Unlike the classic TRIZ contradiction model, which considers two states of a single AP, the Generalized System of Contradictions (GSC) approach examines two states of multiple APs to formulate the Generalized Physical Contradiction (GPC).

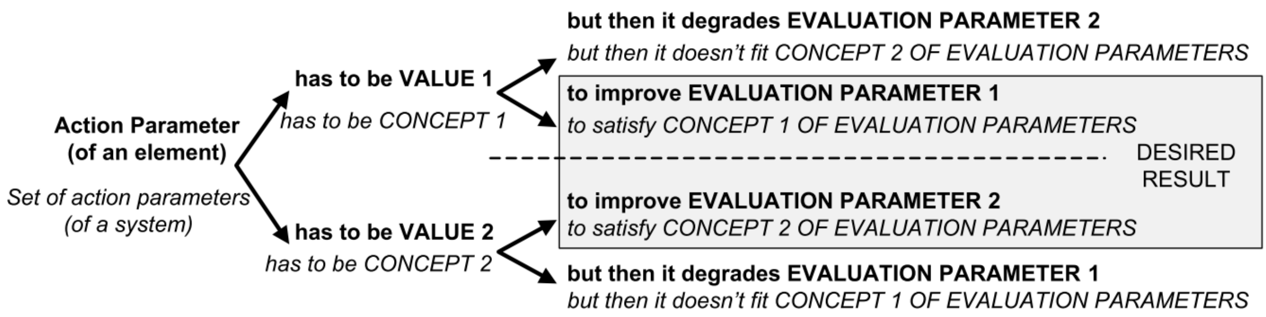

Figure 26: OTSM-TRIZ System of Contradictions (Dubois et al. 2009)

To resolve a technical contradiction, one of the most commonly used tools in TRIZ is the Contradiction Matrix (CM). This matrix consists of 39 parameters, listed on the vertical axis as the parameters to be improved (Improving Parameters, IP), and on the horizontal axis, the parameters that may deteriorate as a result (Avoiding Degradation Parameters, ADP). Each cell in the matrix suggests the most frequently applied inventive principles to resolve such contradictions. In other words, the CM helps identify which of the 40 TRIZ inventive principles (Table 9) have been most successfully used to solve a specific contradiction between two parameters.

Table 9: 40 TRIZ Inventive Principles

1	Segmentation	21	Skipping
2	Taking Out/Separation	22	'Blessing In Disguise'
3	Local Quality	23	Feedback
4	Asymmetry	24	Intermediary
5	Merging	25	Self-Service
6	Universality	26	Copying
7	'Nested Doll'	27	Cheap Short-Living Objects
8	Anti-Weight	28	Mechanics Substitution
9	Preliminary Anti-Action	29	Pneumatics And Hydraulics
10	Preliminary Action	30	Flexible Shells And Thin Films
11	Beforehand Cushioning	31	Porous Materials
12	Equipotentiality	32	Colour Changes
13	'The Other Way Around'	33	Homogeneity
14	Curvature	34	Discarding And Recovering
15	Dynamization	35	Parameter Changes
16	Partial Or Excessive Actions	36	Phase Transitions
17	Another Dimension	37	Thermal Expansion
18	Mechanical Vibration	38	Strong Oxidants
19	Periodic Action	39	Inert Atmosphere
20	Continuity Of Useful Action	40	Composite Materials

Traditional TRIZ method for resolving technical and physical contradictions typically follows a linear process. First, Technical Contradictions (TCs) are identified and converted into Physical Contradictions (PCs), and then solutions are proposed using separation principles, such as separating contradictory demands in space, time, relation, system levels, or parameters. If separation doesn't resolve the contradiction, it may be possible to satisfy both demands simultaneously using the 40 TRIZ inventive principles. If that's not feasible, the contradiction may be bypassed through system transitions, such as transitioning to a subsystem, supersystem, alternative system, or an inverse system (Ko et al. 2015).

In traditional TRIZ-based problem-solving, TCs and PCs are addressed in sequence:

1. Identify and resolve the technical contradiction using the TRIZ contradiction matrix.
2. Convert the technical contradiction into a physical contradiction and resolve it using separation principles (separation in space, time, condition, or system transition).

According to (Coulibaly 2017), TRIZ complements other design tools and methods very well. As a result, numerous researchers have suggested integrating TRIZ with various design tools and methods within the engineering design process. In this study, we integrate TRIZ with the Axiomatic Design (AD) method. The following sections presents our methodology and explains how TRIZ principles are applied to the results of our Lean 5.0 Axiomatic model.

As presented in Chapter III, our methodology consists of three main phases: The first phase, concerning the formulation of Lean requirements and parameters, and second phase, concerning the proposal of the Generalized Axiomatic model for a Lean 5.0 system, are addressed in the previous chapter. In this chapter, we address in detail Phase 3, concerning the formulation and resolution of contradictions that may arise from the integration of Lean 5.0 requirements.

Based on the complementarity analysis between TRIZ and AD, we consider that the parameters identified in Phase 1 serve as the EPs used to analyze potential contradictions and evaluate the performance in the design of a Lean 5.0 system. The second phase results in a list of design parameters (equivalent to APs in our contradiction-resolving methodology) and process variables (equivalent to solution concepts (SCs) in our contradiction-resolving methodology) corresponding to the Lean 5.0 functional requirements.

2. Lean 5.0 Parameter Integration Matrix (L5.0PIM) Methodology

L5.0PIM is initially inspired by two main concepts. Firstly, the concept of generalized system of contradiction based on the use of the concept of Pareto optimums of the binary matrix to extract technical and associated physical contradictions proposed by (Chibane et al. 2021).

Secondly, the concept of Generalized Table of Parameters (GTP) introduced by (Abdellatif et al. 2023). This table can help in understanding complex design problems by modeling and representing quantitative and qualitative data. It serves to extract system conflicts based on the TRIZ problem model. In addition, (Abdellatif et al. 2024) develop a method to integrate the GTP in the inventive design process to extract the most important contradictions to be solved. However, GTP is limited in its focus on the physical parameters of the system, whereas our proposed approach integrates additional parameters related to the manufacturing system, including Lean and I5.0 parameters. GTP has been applied in industrial applications within the mechanical domain.

Although the idea behind our methodology is basically inspired by the GTP methodology presented by (Abdellatif et al. 2023, 2024), L5.0PIM presents many added functionalities compared to GTP, as shown in Table 10.

Table 10: Added Functionalities of our Proposed L5.0PIM Compared to GTP

Criteria	GTP	L5.0PIM
Context	The general context is based on a set of conditions, limits, requirements and constraints, within which the system and the problems to be solved are situated	The general context is based on a set of Lean tools commonly used in industry aligned with I5.0 principles. The objectives and the problems addressed by these tools are already known
Domain	Mechanical systems	Manufacturing systems
Problem	Must be identified before GTP creation	Standard matrix for all the problems
Applicability	Each GTP is specific to a particular case study	Can be applied to different case study
Selection of Parameters	The parameters in the table change depending on the problem	Parameters are selected from the L5.0PIM to match the problem.
Nature of parameters	-Action Parameters (APs) are linked parameters to the global form of the structure, material, and experimental control parameters. -Evaluation parameters (EPs) are linked parameters to solve the potential problem(s)	-APs are extracted based on the combination between Lean Tool FRs and I5.0 principles (Table 8) -EPs are extracted from general Lean requirements (Table 6)
Structure of the table	Each identification of technical contradictions must be referred to the contradiction matrix to study the similarities with the technical parameters of the TRIZ contradiction matrix	Auto identification of physical and technical contradictions: -Each AP in the matrix is related with principles for resolving physical contradictions -Each EP is related to technical parameters of TRIZ contradiction matrix

L5.0PIM consists of a set of generalized Lean parameters which is specifically dedicated to manufacturing domain. Our aim is to identify the possible technical and physical contradictions resulting from the specification of the Generalized Action Parameters (GAPs) that we have extracted from Lean 5.0 Axiomatic model (Examples: DP15: External Changeover; DP16: Tool Removal or Standardization, etc.) and the Generalized Evaluations Parameters (GEPs) extracted from literature (Examples: Cycle time; Environmental Impact, etc.).

As mentioned in the first section, TRIZ follows a sequential approach that may not always be efficient, as technical and physical contradictions are often deeply interconnected. Our proposed approach allows for their simultaneous resolution based on the idea that:

- Technical contradictions often share an underlying physical contradiction. Several technical contradictions can arise from the same contradictory need at a physical level. For example, a manufacturing system may have several conflicts between speed, precision and flexibility, but all may be linked to the same physical contradiction (e.g. a component must be both rigid and flexible).
- Separation principles are general and can resolve many technical contradictions. A solution based on separation in space can resolve various technical contradictions by distributing conflicting features in different areas of the system. Similarly, a separation in time can allow the same element to function differently according to need, eliminating several technical conflicts.

Instead of treating technical and physical contradictions separately, we use the following approach to ensure that both contradictions are resolved within a single design step.

1. Select the APs and propose Generalized Solution Concepts (GSCs) for resolving physical contradictions based on separation principles. The GSCs are broad solution strategies that leverage TRIZ separation principles to handle physical contradictions associated with the selected APs. GSCs rely on the interpretation and analysis of documented cases in the literature, patents, and expert insights. They involve studying instances where separation principles have been successfully applied to similar APs with the same or closely related objectives.
2. Identify the technical contradictions (TCs) by determining the conflicting technical parameters.
3. Find inventive principles that resolve the TCs using the TRIZ CM.
4. Determine whether any of the identified inventive principles align with the four common separation principles. The inventive principles applied to each of the four common separation methods are shown in Table 11 (Hipple 2012).

Table 11: Inventive Principles applied to Separation Methods

Separation Principle	Applied Principles
Separation in space	9. Preliminary anti-action 10. Preliminary action 11. Beforehand cushioning 15. Dynamism 16. Partial or excessive action 18. Mechanical vibration 19. Periodic action 20. Continuity of useful action 21. Skipping 26. Copying 34. Discarding and recovering 37. Thermal expansion
Separation in time	9. Preliminary anti-action 10. Preliminary action 11. Beforehand cushioning 15. Dynamism 16. Partial or excessive action 18. Mechanical vibration 19. Periodic action 20. Continuity of useful action 21. Skipping 26. Copying 34. Discarding and recovering 37. Thermal expansion
Separation between parts and whole	1. Segmentation 5. Merging 6. Universality 8. Counter-weight 12. Equipotentiality 13. "Other Way Around"/ Do it in reverse 22. Blessing in disguise 23. Feedback 25. Self-service 27. Cheap, short living objects
Principles applicable to separation upon condition	28. Mechanics substitution 29. Pneumatics and hydraulics 31. Porous materials 32. Color changes 35. Parameter changes 36. Phase transition 38. Strong oxidants

5. If an inventive principle aligns with a separation principle, we first verify whether the GSC can resolve all the TCs associated with the AP. If so, we proceed with resolving the TCs within the context of the corresponding GSCs. If the selected inventive principle does not align with any separation principles, we then assess whether the GSCs and their corresponding separation principles are better suited to resolving the TCs. If the GSC can resolve only one TC, the prioritization of which TC to resolve first is determined based on the weight assigned to the parameters by the designer.

Figure 27 explains this approach to simultaneously resolving technical and physical contradictions.

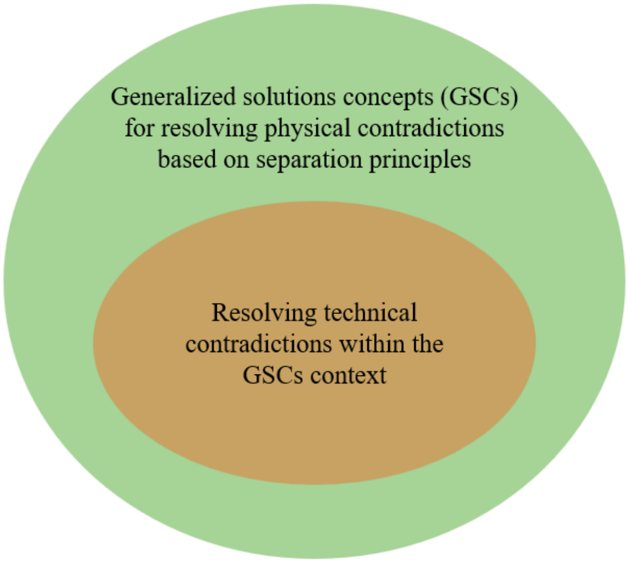

Figure 27: Our Approach to Simultaneously Resolving Technical and Physical Contradictions

L5.0PIM represents an initial initiative to simultaneously extract technical and physical contradictions resulting from the integration of Lean requirements. It also formulates a system of contradictions among various Lean parameters to be integrated into the design phase, while ensuring that these requirements and parameters consistently align with the principles of I5.0.

L5.0PIM is composed of set of generalized Lean parameters that affect the performance of manufacturing or production processes. Figure 28 shows the steps of L5.0PIM methodology. These steps are categorized into two main phases: L5.0PIM filling and problem solving, which will be detailed in the following section. These steps involves gathering data and information from a variety of sources, including scientific databases and expert opinions.

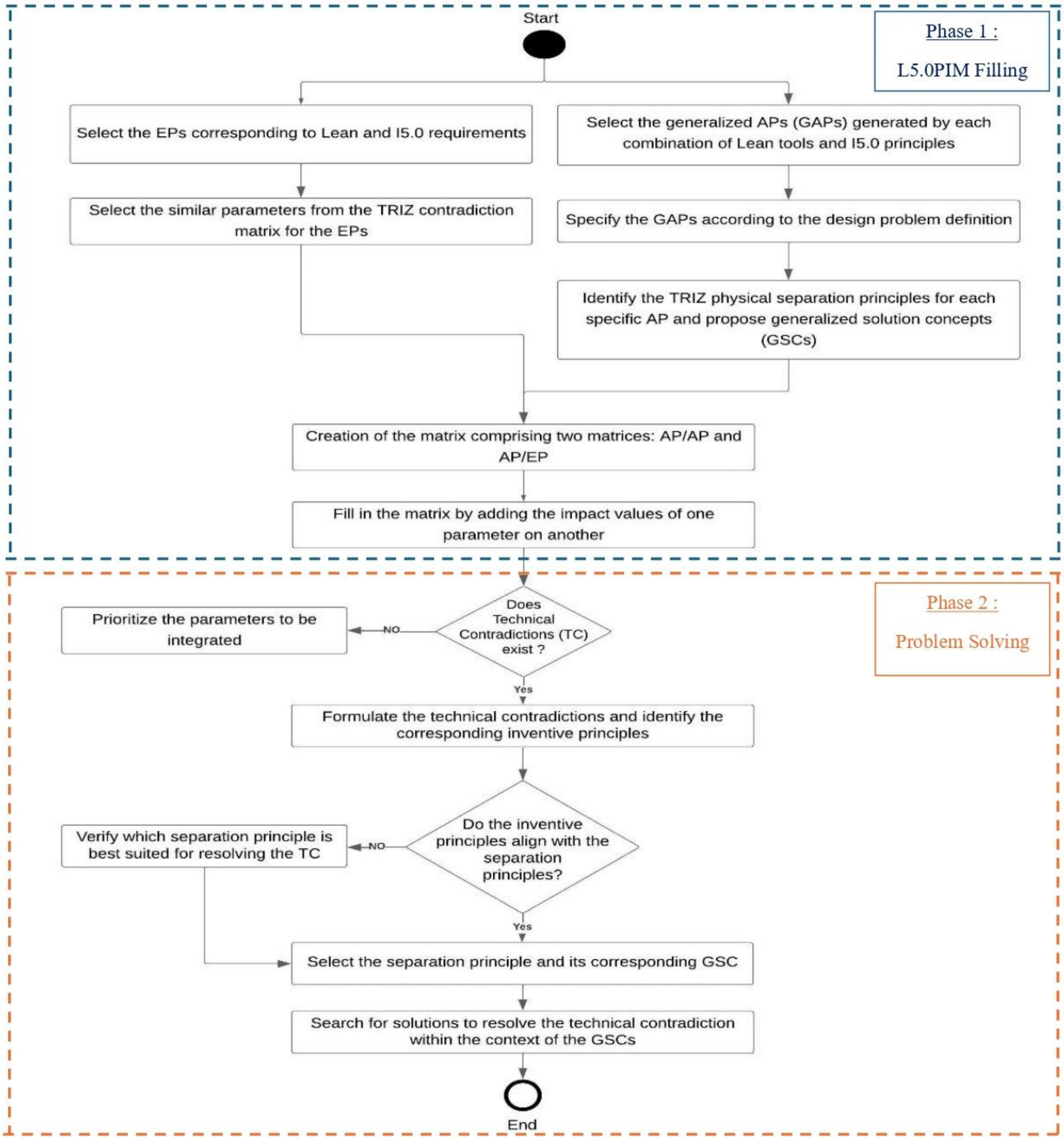

Figure 28: L5.0PIM Methodology

3. L5.0PIM Structure

L5.0PIM begins by selecting a set of Lean tools commonly used by companies, then extracting the relevant parameters for each tool in an I5.0 context. Figure 29 shows the structure of our matrix, including some of the identified parameters. It is important to note that the list of parameters in our matrix is not exhaustive; it represents an initial effort to develop our current perspective, and the approach outlined here is considered an initial version. This version is intended as a starting point and may be refined and expanded over time, based on further research and evolving contextual factors. We continue to add new parameters as we or the designers recognize their benefits. It can also serve as an initial model for other researchers to contribute additional parameters based on their areas of expertise.

							SAP \ Objective				Specific EP (SEP) Min/Max	Min/Max	Min/Max	Min/Max
Lean Tool	Lean 5.0 FRs	Generalized AP (GAP)	Specific AP (SAP)	GSCs for GAPs	Separation Principles and GSCs for SAPs	Opposite values for SAP	SAP 1	SAP2	SAP3	SAPn	SEP1	SEP2	SEP3	SEPn
SMED	Sustainable Rapid Changeover	1-External Changeover	SAP 1	Quick-Change Fixtures and Mechanism	*Identified based on Problem definition*	V=Max		-1 /0/+1	-1 /0/+1	-1 /0/+1	-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
						$\bar{V}$=Min					-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
	Resilient Rapid Changeover	2-Modular Equipment Design	SAP 2	Additive Manufacturing		V=Max	-1 /0/+1		-1 /0/+1	-1 /0/+1	-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
						$\bar{V}$=Min					-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
	Human-Centric Rapid Changeover	3-Digital Work Instructions	SAP 3	Augmented Reality Guides		V=Max	-1 /0/+1	-1 /0/+1		-1 /0/+1	-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
						$\bar{V}$=Min					-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
5S	Sustainable Minimal Tool Use	4-Tool Removal or Standardization	SAP 4	Multi-Functional Tools		V=Max								
						$\bar{V}$=Min								
	Resilient Minimal Tool Use	5-Tool Availability	SAP 5	Built-In Tool Functions		V=Max								
						$\bar{V}$=Min								
	Human-Centric Minimal Tool Use	6-Identification and the localization of objects	SAP 6	Virtual tool placement guide		$\bar{V}$=Min								
						$\bar{V}$=Min								
TPM	Sustainable Easy Maintenance	7-Customizable Alerts	SAP 7	Visual Management and Metrics		V=Max								
						$\bar{V}$=Min								
	Resilient Easy Maintenance	8-Automated Monitoring and Diagnostics	SAP 8	Predictive Maintenance Algorithms		V=Max								
						$\bar{V}$=Min								
	Human-Centric Easy Maintenance	9-Operators and Maintenance Specialists Interaction	SAP 9	Reality and virtual Simulation		V=Max								
						$\bar{V}$=Min								
Poka-Yoke	Sustainable Error Prevention	10-Automatic Error Detection	SAP 10	Error-Proofing Devices and Mechanisms		V=Max								
						$\bar{V}$=Min								
	Resilient Error Prevention	11-Prediction Based On Past Data	SAP 11	AI Algorithms		V=Max								
						$\bar{V}$=Min								
	Human-Centric Error Prevention	12-Provide Operators With Real-Time Feedback and Guidance	SAP 12	AR Guidance for Operators		V=Max								
						$\bar{V}$=Min								
JIT			SAP n											
Heijunka			SAP n											
Kanban			SAP n											
VSM			SAP n											
Similar parameters of the TRIZ Contradiction Matrix											25, 33, 36…	26,39,21 …	19, 22, 23 …	…

Figure 29: L5.0PIM Structure

In the following sections, we outline the steps and key elements for creating L5.0PIM.

3.1 Evaluation Parameters and their similar Parameters from TRIZ CM

This section encompasses the two steps: "Select the EPs corresponding to Lean and I5.0 requirements" and "Select the similar parameters from the TRIZ CM for the EPs" of the L5.0PIM methodology.

Given the wide range of Lean 5.0 EPs identified (More than 100 EPs), we decide to categorize similar or interconnected parameters into Generalized EPs (GEPs). When using the L5.0PIM, we provide the designer with a list of GEPs, helping them frame the performance aspects they want to improve, such as cycle time, productivity, environmental impact, etc. Then, they specify which performance parameters are most relevant to their problem by selecting from the Specific EPs (SEPs) for each GEP. For example, for the GEP "Cycle Time", the SEPs could include Reconfiguration Time, Waiting Time, Material Search Time, etc. (See Table 12).

We conduct a detailed analysis to identify similarities between each GEP and the technical parameters found in the TRIZ CM. This mapping facilitates a more structured and efficient approach to contradiction resolution. By aligning GEPs with TRIZ parameters, we streamline the process, enabling designers to quickly identify relevant inventive principles. Once a TC is formulated, our methodology allows for the direct selection of inventive principles corresponding to the intersection of these conflicting parameters in the TRIZ CM. This targeted approach accelerates the resolution process by eliminating the need for extensive trial-and-error iterations, guiding designers toward systematic and effective solutions.

The GEPs are classified into three categories representing the principles of I5.0: Sustainability, Resilience and Human-Centricity. Table 12 represents the specification of the GEPs into the SEPs, as well as a list of the corresponding TRIZ technical parameters from the CM.

Table 12: Lean 5.0 Generalized EPs

Generalized Evaluation parameter (GEP)	Specific Evaluation Parameters (SEP)	TRIZ Parameters from the CM
	Sustainability	
EP1- Cycle time	-Reconfiguration Time -Changeover Time -Operator Idle Time -Waiting Time -Handling Time -Material Search Time -Inspection Time	**-Waste of Time (25):** Most of the cycle time sub-parameters relate to time lost during the various stages of the production process. **-Ease of Use (33):** The simpler the process or equipment reconfiguration, the less time it takes, which helps reduce cycle time. **-Product Complexity (36):** More complex products or processes require longer changeover and handling times, which has a direct impact on cycle time by increasing the time required to complete production tasks. -**Manufacturing Accuracy (29)**: Accurate handling and processing minimize errors and rework, reducing the time spent on corrections and contributing to a shorter cycle time. **-Loss of Information (24):** Can be related to waiting time and material search time, where inefficiencies in information handling can cause delays. -**Duration of Action of the Mobile Object (15):** Cycle times are directly related to the time it takes materials or products to progress through all stages of the production process.
EP2- Productivity	-Equipment Capacity -Utilization Rate -Value-Adding Time -Takt Time	**-Quantity of Substance (26)**: Relates to how much equipment can process, which is essential for evaluating productivity in terms of capacity and output. **-Productivity (39)**: Directly relevant as it measures the efficiency of using resources, time, and equipment to produce goods. **-Power (21)**: Reflects the energy and effectiveness of resource use, which is integral to maintaining high utilization rates and consistent productivity. **-Waste of Time (25)**: Central to productivity, as reducing wasted time enhances the proportion of time spent on value-adding activities. **-Manufacturing Accuracy (29)**: Ensures that processes are efficient, reducing errors and rework, thereby maximizing productivity. **-Ease of Realization (32)**: Simplifying processes makes it easier to achieve productivity goals, as less complex systems are more efficient and easier to manage.
EP3- Environmental Impact	-Resource and Energy Efficiency -Waste Utilization -End-of-Life Product Recovery	**-Energy Used by the Mobile Object (19)**: Energy consumption is directly related to environmental impact, particularly through the carbon footprint and emissions. **-Energy Loss (22)**: Minimizing energy loss is crucial for improving resource and emissions efficiency, directly impacting environmental sustainability.

	-Post-Use Waste Conversion -Waste Identification -Green Material Usage -Resource and Emissions Efficiency -Consumption Efficiency -Resource and Waste Tracking -Disassembled Part -Carbon Footprint	**-Loss of Substance (23)**: Effective waste management, including waste utilization and post-use conversion, reduces the loss of valuable materials and minimizes environmental harm. **-Loss of Information (24)**: Proper tracking of resources, emissions, and waste ensures that environmental impacts are minimized through better management and control. **-Quantity of Substance (26)**: Efficient use of materials, especially green materials, directly reduces the environmental impact by minimizing resource consumption and waste. **-Factor Harmful to the Object (30)**: Focuses on reducing detrimental effects like pollution and resource depletion, which are key to lowering environmental impact. **-Ease of Realization (32)**: Simplifying processes related to recycling, waste conversion, and recovery makes it easier to adopt environmentally friendly practices.
EP4- Cost Efficiency	-Cost Per Unit -Maintenance Cost -Transportation Cost -Repair Resource Efficiency -Material Usage Efficiency -Energy Cost Efficiency	**-Quantity of Substance (26)**: Efficient material usage reduce costs by minimizing the amount of raw material and energy required. **-Loss of Substance (23)**: Reducing waste and inefficiencies in material usage, repair processes, and transportation lowers costs by ensuring that more resources are converted into usable output. **-Energy Used by the Mobile Object (19)**: Energy costs, particularly in transportation and production, are a significant factor in overall cost efficiency. Optimizing energy use reduces these costs. **-Energy Loss (22)**: Minimizing energy loss in production and transportation processes directly reduces costs, contributing to improved cost efficiency. **-Maintenance (34)**: Effective maintenance and repair processes reduce downtime and the costs associated with equipment upkeep, directly impacting cost efficiency. **-Reliability (27)**: High reliability of equipment and processes reduces the need for frequent repairs and maintenance, thereby lowering associated costs. **-Ease of Realization (32)**: Simplifying processes, whether in repairs, production, or transportation, reduces the time and resources required, thus lowering costs and improving efficiency. **-Productivity (39)**: Higher productivity spreads fixed costs over more units, reducing the cost per unit and improving overall cost efficiency.
EP5- Quality and Error Management	-Error Detection Responsiveness -Failure Detection Accuracy -Variation -Quality -Scrap Rate -Defect Rate -Rework Rate -Process Capability Index (Cpk) -First Pass Yield (FPY)	**-Accuracy of Measurement (28)**: Accurate detection and measurement are essential for identifying and managing defects and errors in the production process, ensuring high-quality output. **-Accuracy of Manufacturing (29)**: Maintaining high manufacturing accuracy directly impacts product quality by ensuring that processes are precise and consistent. **-Reliability (27)**: Reliable production processes minimize the occurrence of errors and defects, leading to higher quality products and reduced need for rework. **-Loss of Substance (23)**: Reducing material waste through effective quality control and error management ensures that more resources are converted into usable products. **-Factor Harmful to the Object (30)**: Managing harmful factors that could affect the product or process is crucial for maintaining high quality and minimizing defects.

		-Induced Adverse Factors (31): Identifying and mitigating factors that could introduce defects or errors into the production process helps maintain product quality and consistency. **-Ease of Realization (32)**: Simplifying processes reduces the likelihood of errors, making it easier to maintain high quality and minimize the need for rework.
Resilience		
EP6- Complexity	-Number of components per product -Number of configuration settings -Interdependencies Between Components -Variability in Production Processes	**-Product Complexity (36)**: The number of components and configuration settings directly impacts the overall complexity of the product. **-Volume of the Moving/Static Object (07/08)**: As the number of components increases, so does the potential volume of the product. Larger or more complex products require more intricate design and assembly processes. **-Ease of Realization (32)**: Complexity in the number of components and configuration settings can make the product more difficult to realize or produce. **-Complexity of Pilotage (37)**: The number of configuration settings affects how complex it is to control or operate the product. More settings can lead to greater difficulty in ensuring the product functions correctly and efficiently. **-Shape (12)**: The configuration settings often affect the shape or form of a product, adding to its complexity. Complex shapes may require more advanced manufacturing techniques, increasing the overall difficulty of production. **-Object Stability (13)**: More configuration settings can impact the stability of the product, especially if these settings are not well managed or integrated, leading to potential challenges in maintaining product performance.
EP7- Reliability and Maintenance	-Overall Equipment Effectiveness (OEE) -Equipment Availability -Tool Availability -Mean Time to Repair (MTTR) -Mean Time Between Failures (MTBF) -Downtime -Failure Detection Accuracy -Preventive Maintenance -Predictive Maintenance	**-Reliability (27)**: Directly related to the reliability of the equipment. High reliability ensures that equipment operates consistently and efficiently with minimal failures. **-Ease of Realization (32)**: Equipment that is easy to maintain and repair (low MTTR) is more likely to be available and reliable, contributing to overall efficiency. **-Object Stability (13)**: Stable and well-maintained equipment leads to higher reliability and availability, reducing the likelihood of failures and downtime. **-Accuracy of Measurement (28)**: Accurate detection of failures and predictive maintenance relies on precise measurement and monitoring, which is essential for maintaining high reliability. **-Factor Harmful to the Object (30)**: Target factors that could harm the equipment to ensure its longevity and consistent performance. **-Waste of Time (25)**: Downtime is a form of wasted time in production. Reducing downtime through effective maintenance practices is essential for maximizing operational efficiency.
EP8- Flexibility and Adaptability	-Supply Chain Reconfigurability -Process Reconfigurability -Workplace Adaptability	**-Adaptability (35)**: Reflects the system's ability to handle variations and changes effectively. **-Ease of Realization (32)**: Parameters that impact the ease of implementing changes or adjustments contribute to overall flexibility. This includes factors like workplace layout, production means mobility, and process reconfigurability.

	-Mobility of Production Means -Scalability -Customization Efficiency -Feasibility -Resource Flexibility	**-Object Stability (13)**: Maintaining stability while adapting to new conditions or requirements is essential for effective flexibility. This includes ensuring that changes do not compromise the stability or performance of the system or product. **-Shape (12)**: Flexibility in design and layout often involves changes in shape or configuration, impacting the ability to adapt to different needs or requirements. **-Reliability (27)**: For a system to be flexible and adaptable, it must remain reliable across different conditions and configurations. Ensuring that adaptations do not negatively affect reliability is essential for maintaining overall efficiency.
Human-Centricity		
EP9- Safety and Ergonomics	-Safety -Personal Protective Equipment -Emergency Response Systems -Ergonomic -Incident Rate -Work Area Cleanliness	**-Factor Harmful to the Object (30)**: Safety involves identifying and mitigating harmful factors that could lead to accidents or injuries. This includes ensuring that work environments and processes are designed to minimize risks. **-Induced Adverse Factors (31)**: Effective safety and ergonomics management involves addressing adverse factors that could negatively impact safety and comfort. Reducing these factors helps prevent incidents and improve overall working conditions. **-Ease of Realization (32)**: Implementing safety and ergonomic measures should be practical and straightforward. Systems and processes need to be designed for easy integration of safety features and ergonomic improvements. **-Ease of Use (33)**: Ergonomics focuses on making tools, equipment, and work environments easy to use and comfortable for workers. **-Shape (12)**: Ergonomic design often involves adjusting the shape and configuration of tools and workspaces to fit human needs and reduce discomfort. **-Reliability (27)**: Reliable safety systems and ergonomic solutions are essential for maintaining a safe and efficient work environment.
EP10- Human Factors and Communication	-Human Contribution -Cobots Utilization -Communication Efficiency -Operator Alert Effectiveness -Feedback Mechanisms	**-Ease of Use (33)**: Human factors and communication involve ensuring that systems are easy to use and interact with. This includes designing user-friendly interfaces and ensuring that human operators can effectively engage with technology. **-Adaptability (35)**: Systems and processes should be adaptable to human needs and capabilities, including the ability to work effectively with cobots and adjust to different operational contexts. **-Object Stability (13)**: Reliable and stable systems support better human performance and effective communication, reducing errors and improving overall efficiency. **-Loss of Information (24)**: Effective communication systems aim to minimize information loss and ensure that critical information is accurately conveyed to all relevant parties. **-Degree of Automation (38)**: The integration of automation, such as cobots, should enhance human performance and collaboration, reflecting the degree of automation in the system.

These preparatory steps for selecting the EPs and their corresponding parameters from the TRIZ CM are accompanied by the selection of APs, their specification according to the design problem definition, and the identification of corresponding GSCs. These steps are detailed in the following section.

3.2 Action Parameters, Separation Principles and Generalized Solution Concepts

This section encompasses the three steps: "Select the Generalized APs (GAPs) generated by each combination of Lean tools and I5.0 principles", "Specify the GAPs according to the design problem definition" and "Identify the TRIZ physical separation principles for each Specific AP (SAP) and propose Generalized Solution Concepts (GSCs)" of the L5.0PIM methodology.

L5.0PIM is developed as a generalized framework to ensure adaptability across different design challenges. However, when applying it to real-world design problems, designers must first define the specific issues they seek to resolve. This initial step is crucial, as it allows for the alignment of generalized parameters with the unique characteristics of the design problem, ensuring a more effective and tailored resolution process. This begins with providing a clear and detailed problem definition that outlines the context of the design challenge. Based on these defined problems, designers can then select the relevant APs applicable to their context. These parameters are adapted to fit the specific situation, transitioning from generalized parameters to context-specific ones, and the opposing values associated with each parameter are identified. LP5.0PIM consists of two types of APs: Generalized APs (GAPs) and Specific APs (SAPs).

The GAPs consist of generalized Design Parameters (DPs) derived from the Lean 5.0 Axiomatic model. Each parameter reflects a FR that integrates both Lean tool and I5.0 principle. The general nature of these parameters allows for their adaptability to various systems and design challenges. Whether applied to manufacturing systems or digital transformation efforts, GAPs act as flexible templates that can be customized to specific contexts. This adaptability is key to addressing the unique requirements of different systems while maintaining consistency in approach. Furthermore, GAPs foster innovation by encouraging designers and decision-makers to think beyond traditional constraints.

SAPs are tailored design parameters derived from GAPs to address technical needs within a defined design problem. While GAPs provide a high-level, adaptable framework that integrates Lean and I5.0 principles, SAPs translate these generalized parameters into concrete, actionable technical parameters suitable for implementation in specific contexts. In the design process, SAPs serve as the bridge between theoretical models and practical applications. Designers begin by analyzing the list of GAPs, which represent broad, adaptable guidelines. These GAPs are then contextualized based on the unique requirements of the design problem at hand. By considering the FRs, constraints, and objectives of the system, designers refine and specify GAPs into SAPs, ensuring alignment with technical, operational, and strategic goals.

L5.0PIM consists of two types of Generalized Solution Concepts (GSCs): GSCs for GAPs and GSCs for SAPs. GSCs for GAPs represent the Process Variables (PVs) identified from our Axiomatic model. These GSCs serve as directional guidelines that can contribute to resolving contradictions. They outline the tools and technologies that may be utilized in developing a solution.

GSCs for SAPs provide a structured framework for resolving the physical contradiction associated with a given SAP based on separation principles. The opposite value of each SAP or its physical characteristics can define the physical contradiction, which can then be addressed through appropriate separation principles.

For each applicable separation principle, we propose a corresponding GSC that establishes a guiding framework for resolving the technical contradictions related to the same SAP. This approach ensures that TCs emerging from the design problem are systematically addressed within the broader resolution of the PC.

Currently, the identification of separation principles and their corresponding GSCs relies on manual interpretation and analysis of documented cases in the literature, patents, and expert insights. This process involves studying instances where separation principles have been successfully applied to similar APs that share the same or closely related objectives.

By incorporating AI tools, we aim to enhance the efficiency, accuracy, and scalability of L5.0PIM, making it a more intelligent and adaptive tool for resolving contradictions in complex design problems. Achieving this vision will require extensive testing and validation through multiple real-world case studies. This testing is crucial to ensuring the effectiveness, reliability, and adaptability of the proposed automated approach. By systematically evaluating the framework in diverse practical scenarios, we can refine its functionality and optimize its performance.

3.3 Creation and Filling of the Matrix

L5.0PIM is composed of two matrices APs/APs and APs/EPs. The importance of the APs/APs matrix is expressed as follows: The relationship between APs means that the integration of one AP can help or hinder the integration of the other. In case they share the same objective, the integration of one AP can fulfill the objective of the integration of another parameter and can lead to resolve one contradiction to fulfill the objective of two APs.

The use of L5.0PIM depends on designers determining which parameters are relevant to their specific challenges, specifying which APs are appropriate to their design problems and which parameters they wish to improve. They can then analyze and select the parameters from our matrix that seem relevant to their problem. This step is followed by specifying the generalized parameters according to the problem definition provided by the designer, in order to check for contradictions by filling the matrix.

Filling the matrix with the value that describes the significance of a relationship between two parameters should be based on expert opinion via semi-structured interviews or questionnaire surveys. The filling of the matrix consists of evaluating the impact of each AP on other APs and assessing its impact on the different EPs. The value could be: +1 → When Parameter A increases, then Parameter B increases, as well. -1 → When Parameter A increases, then Parameter B decreases. 0 → No influence of parameter A on parameter B. Sometimes, if no answer is available, we can use a (?) indicating that further research is required, either through literature review or AI analysis, to explore the relationship in depth. For certain parameters, the answer may be context-specific, and providing a general statement may not be relevant. In such cases, we can include two possible answers within the same box, reflecting the different possibilities based on the specific context of the study.

After filling in the matrix, the next steps include identifying the contradictions and proceeding with their resolution. The designer can consult our guide on separation principles, GSCs, and TRIZ technical parameters from the CM related to the EPs to find a solution. When multiple TCs are present, the designer evaluates each parameter and assigns it a weight to identify the most significant contradictions. The following section provides an explanation of the formulation and resolution process to be followed in L5.0PIM.

3.4 Formulating and Resolving Contradictions

Once the matrix is filled, we analyze whether the values of the APs have a positive or negative impact on the EPs in relation to their predefined objectives, with the aim of identifying contradictions. To make these contradictions more visually clear, we use a color-coded system in the matrix:

- Green cells indicate that an increase in the AP contributes positively to achieving the objective set for the EP.
- Red cells signify that an increase in the AP negatively affects the EP, working against its objective.

If all the cells in the AP row are green, it means that no contradiction exists. However, if both green and red cells are present, this indicates the coexistence of technical and physical contradictions, forming a system of contradictions.

The resolution process relies on two key components: Inventive principles for resolving TCs and GSCs derived from separation principles associated with SAPs. Once the TCs are defined, we look for the corresponding parameters of TRIZ CM that match the contradictory EPs and select the relevant inventive principles from the CM. Next, we check whether any of the selected inventive principles align with the separation principles identified in the beginning. If such an alignment exists, the TC is resolved within the context of the corresponding GSC. If no direct alignment is found, we assess whether the GSCs and their associated separation principles provide a more suitable approach for resolving the TC.

When multiple inventive principles are available for resolving a TC, the one most aligned with the identified separation principle and its corresponding GSCs is selected. If one inventive principle can resolve multiple TCs associated with the same SAP, it should be applied in conjunction with the relevant GSC. Otherwise, each TC must be resolved individually.

In the following section, we provide an illustrative application to clarify the contradiction formulation in L5.0PIM.

4. Illustrative Example Applied to the SMED Tool: Contradictions Formulation

In the following, we present an extrait of the L5.0PIM to explain its concept. This extract is derived from the SMED tool (Gdoura et al. 2024b). We have considered only a subset of the parameters associated with SMED in this illustrative study, which was used to test the method using a minimal number of parameters for rapid evaluation.

Table 13 contains four of the APs we have identified in connection with the parameter "DP15- External Changeover" corresponding to FR15 "Design for Sustainable Rapid Changeover" (See Chapter III, Section 3.3), as well as their description and their corresponding separation principles and GSCs.

Table 13: SMED APs and Separation Principles

APs- SMED	Description	Separation Principles and GSCs
AP1-External Setup	Activities that can be carried out while the machine is still running. This may involve preparing tools for the next pass, gathering the necessary materials and reconfiguring settings.	1- Separation in Space (dedicated setup area), 2- Separation in Time (parallel setup), 4- Separation in System Levels (quick-change tooling + standard tools)
AP2- Standardization	Standardized work during the setup. It includes specific instructions, tools needed, and an expected completion time for Machine Setup Time Reduction in a Machining Process	3- Separation in Relation (Standardization with Flexibility Options), 4- Separation in System Levels (Modular Design)
AP3-Number of setups	Frequency of changing production lines or equipment configurations	2- Separation in Time (group similar products for setup), 4- Separation in System Levels (hybrid setup process with manual + automation)
AP4-Degree of Adjustments	This parameter represents the extent to which we modify existing installation procedures. This may involve minor adjustments or a complete overhaul of the change steps	1- Separation in Space (dedicated adjustment area), 2- Separation in Time (pre-calibrated components), 3-Separation in Relation (self-adjusting mechanisms + manual fine-tuning)

We select four out of 10 GEPs: GEP1- Cycle time, GEP2- Productivity, GEP6- Complexity and GEP8- Flexibility and Adaptability. The selection of these parameters is based on our estimation that they can be considered as one of the most important parameters related to the SMED tool example. When using the full matrix in a case study, all parameters must be included, and any possible contradictions between the APs and the various EPs must be identified.

Based on our literature review, and the answers of the AI, we have fill the matrix and identified the impact value of the APs/APs and APs/EPs. Figure 30 shows an extrait of L5.0PIM, contains 4 APs and 4 EPs related to SMED tool. For V=Max, the green cells show that the increase of the AP meets the objective identified in the EP. The red cells indicate that the increase of the AP has a negative effect and an impact against the objective of the EP. For $\overline{\nabla}$ =Min, the green cells show that the decrease in the AP meets the objective identified in the EP. The red cells indicate that the decrease of the AP has an impact against the objective of the EP. Each AP is accompanied by the corresponding physical principles, and each EP is matched by the TRIZ technical parameter.

					Action Parameters					Evaluation Parameters				
Objective										**Min**	**Min**	**Max**	**Max**	**Min/ Max**
	Lean Tool	Separation principles	Valeur		AP1	AP2	AP3	AP4	APn	EP1	EP2	EP3	EP4	EPn
Action Parameters	**SMED**	**1,2,4**	V=Max	AP1		1	-1	-1		-1	+1	+1	+1	+1/0/-1
			$\bar{V}$=Min	AP1						+1	-1	-1	-1	
		3,4	V=Max	AP2	-1		-1	-1		-1	-1	-1	+1	
			$\bar{V}$=Min	AP2						+1	+1	+1	-1	
		2,4	$\bar{V}$=Max	AP3	1	-1		+1		+1	+1	+1	-1	
			$\bar{V}$=Min	AP3						-1	-1	-1	+1	
		1,2,3	V=Max	AP4	-1	-1	+1			+1	+1	+1	-1	
			$\bar{V}$=Min	AP4						-1	-1	-1	+1	
	JIT, 5S, VSM, Kanban, Poka-Yoke, TPM and Heijunka			APn										
Parameters of the TRIZ Contradiction Matrix										15	36	35	39	

Example of Physical Contradiction

Example of Technical Contradiction

Figure 30: Extrait of L5.0PIM related to SMED Tool

Taking the example of the SMED tool parameters as part of the complete list of parameters in our matrix, we have identified four contradictions shown in Table 14.

Table 14: Contradictions founded in SMED Example

		Lean EPs	
Lean APs		☺	☹
AP1-External Setup	V=Max	EP1- Cycle Time (Min); EP3-Flexibility (Max); EP4- Productivity (Max)	EP2- Complexity (Min)
	$\bar{V}$ =Min	EP2- Complexity (Min)	EP1- Cycle Time (Min); EP3-Flexibility (Max); EP4- Productivity (Max)
AP2-Standardization	V=Max	EP1- Cycle Time (Min); EP2- Complexity (Min); EP4- Productivity (Max)	EP3-Flexibility (Max)
	$\bar{V}$ =Min	EP3-Flexibility (Max)	EP1- Cycle Time (Min); EP2- Complexity (Min); EP4- Productivity (Max)
AP3-Number of setups	V=Max	EP3-Flexibility (Max)	EP1- Cycle Time (Min); EP2- Complexity (Min); EP4- Productivity (Max)
	$\bar{V}$ =Min	EP1- Cycle Time (Min); EP2- Complexity (Min); EP4- Productivity (Max)	EP3-Flexibility (Max)
AP4-Degree of Adjustments	V=Max	EP3-Flexibility (Max)	EP1- Cycle Time (Min); EP2- Complexity (Min); EP4- Productivity (Max)
	$\bar{V}$ =Min	EP1- Cycle Time (Min); EP2- Complexity (Min); EP4- Productivity (Max)	EP3-Flexibility (Max)

Taking the example of contradictions related to AP1. Figure 31 shows its system of contradiction.

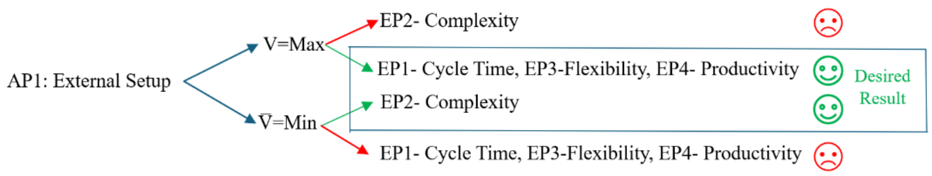

Figure 31: Contradiction System of SMED Parameters

To resolve TCs, the TRIZ principles corresponding to the interaction of the two technical parameters related to the EPs are sought. Each AP is associated with GSC based on separation principles for resolving physical contradictions, thereby allowing for the direct search of a solution to simultaneously resolve both physical and technical contradictions. We first verify whether the GSC can resolve all the TCs associated with the AP. If not, the prioritization of contradictions is determined based on the weight assigned to the parameters by the designer.

In this illustrative example, we focused on the steps of contradiction formulation without exploring the resolution process. To proceed with the resolution, it is necessary to specify the parameters in relation to a real design problem. The application of all the steps of L5.0PIM is presented in the chapter V.

Conclusion

In this chapter, we introduced a new methodology for identifying, formulating and resolving contradictions arising from the integration of multiple Lean 5.0 requirements, entitled "Lean 5.0 Parameter integration Matrix". This matrix is composed of generalized Lean 5.0 parameters that can be considered as a flexible toolbox to be applied into different design scenarios. This adaptability is essential when the exact nature of the problems has yet to be determined. This methodology can be considered a guideline for designers to solve potential contradictions arising from the integration of Lean 5.0 requirements during the design phase and to avoid the repercussions of these contradictions in the future system, which could lead to various problems.

The problem-solving phase in this matrix adopts an approach that simultaneously addresses both physical and technical contradictions within a unified design step. It begins by proposing Generalized Solution Concepts (GSCs), derived from separation principles, which serve as guidelines for resolving physical contradictions. Once the GSCs are established, inventive principles for resolving technical contradictions are identified and applied within the context of the GSCs.

Chapter V: Application of L5.0PIM in Additive Manufacturing Systems: Case Study

Introduction

To demonstrate the relevance of our proposed methodology, this chapter presents a case study on the application of L5.0PIM within the Additive Manufacturing System (AMS). Based on the results of the proposed Lean 5.0 Axiomatic model, we tailored three of the proposed FRs to derive functionalities suitable for integration into the AMS, aiming to improve the current process. By analyzing and resolving the different contradictions in the AMS, we propose inventive solutions to redesign the existing AMS. The results demonstrate a reduction in impression time, material consumption and post-processing complexity, as well as an improvement in part quality and the removal of humans from dangerous and repetitive tasks.

This case study represents an initial effort to gather parameters related to AMS with the goal of introducing a L5.0PIM for this specific manufacturing system. This application outlines the process of collecting and adapting parameters within a manufacturing system, based on the results of the proposed Lean 5.0 Axiomatic model.

1. Additive Manufacturing Process

Additive Manufacturing (AM) represents a promising solution for mass production that aligns with environmental sustainability goals. By minimizing material waste and reducing the need for traditional tooling, AM offers a more resource-efficient approach to production that directly reduces environmental impact. By focusing on system design, AM can be optimized to maximize these benefits in mass production contexts, potentially achieving both economic feasibility and ecological responsibility, in alignment with Lean and Industry 5.0 (I5.0) principles.

AM originates from the need to create structures with customized architectures tailored to specific applications. This process is characterized by a layer-by-layer fabrication approach, enabling precise and complex geometries that are difficult to achieve with traditional manufacturing methods. Figure 32 outlines the fundamental principles and sequential steps involved in the AM process.

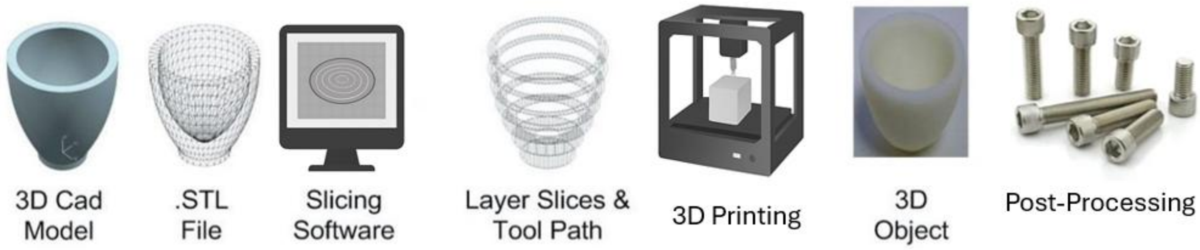

Figure 32: Additive Manufacturing Process

In this case study, we analyze the current Additive Manufacturing System (AMS), specifically the fabrication process for prototyping a knee Handiski prosthesis. Our analysis reveals multiple issues within the existing process. To address these challenges, we leverage the research findings from our Lean 5.0 Axiomatic model and we apply the L5.0PIM methodology to enhance the overall performance of the AMS.

2. L5.0PIM Application

Our application involves adapting the generalized Functional Requirements (FRs) identified in the Lean 5.0 Axiomatic Model, with a primary focus on reducing time and material waste in Additive Manufacturing Systems (AMS). We specifically focus on the three FRs: 1) FR11 “Design for Sustainable Pull Production”; 2) FR15 “Design for Sustainable Rapid Changeover”; and 3) FR16 “Design for Sustainable Minimal Tool Use”, from the first facet of our Lean 5.0 generalized Axiomatic model, FR1 “Design a Sustainable Lean Manufacturing System”. Our analysis of the AMS is made in the context of producing mechanical parts through 3D printing for knee prostheses designed for Handisport applications, particularly skiing. The previous impression process of prototypes developed in our laboratory revealed various gaps and issues that need to be addressed. These challenges are outlined below, along with the corresponding solutions we propose. The goal is to identify the key requirements and parameters necessary to redesign and improve the performance of the current AMS.

The initial step involves identifying and analyzing key issues in the printing process of the previous prosthesis. These challenges are not limited to this specific product but extend to other parts produced within the AMS. Through this analysis, we prioritize three critical problems that have the most significant impact in terms of time and material waste. In the following, we analyze the current printing process and systematically apply the L5.0PIM methodology to identify and resolve various contradictions, with the goal of improving the existing system. Figure 33 presents a series of questions that guide the application of L5.0PIM in filling out the matrix, followed by the identification and resolution of contradictions.

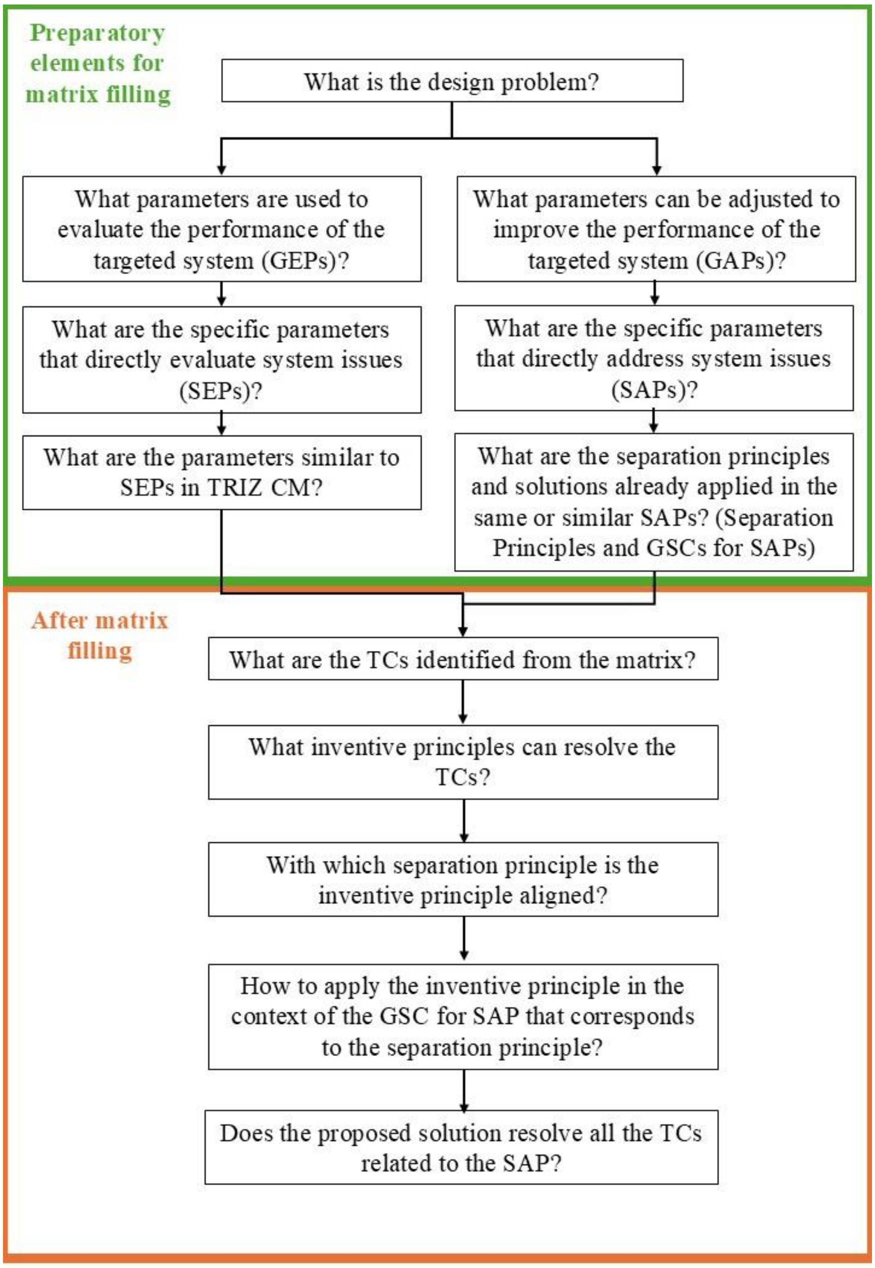

Figure 33: Key Questions Guiding L5.0PIM

2.1 Evaluation Parameters and their Similar Parameters from TRIZ CM

To effectively enhance the current AMS, it is essential to begin with a clear understanding of the challenges addressed. This involves defining the problem in detail and identifying key Evaluation Parameters (EPs) that will guide the analysis and improvement efforts. We start by describing the problem to identify the EPs.

In AM processes, particularly in the production of complex parts like prostheses or mechanical components, several challenges arise related to the optimization of design and production processes. These challenges primarily focus on achieving the desired part quality, while also minimizing impression time, reducing material usage, and simplifying post-processing complexity.

The current process involves considering the variable fill rate, which allows for an increase in the volume of empty spaces. This parameter can be referred to as “infill voids” or “internal voids”. These are the gaps or spaces within the internal structure of a printed part that are not filled with material, which can occur depending on the infill density and pattern used during printing. The incorporation of voids in the design to reduce material consumption, but this often creates challenges in maintaining structural integrity and part quality.

The addition of support structures during printing prevents deformation or collapse but increases material usage, extends production time, and complicates post-processing due to the need for careful removal. Additionally, the incorporation of inserts is essential for enhancing the functionality of the part, but it typically requires post-production modifications, such as manual insertion or drilling, which can affect part quality and consistency and introduce additional handling complexity.

Building on this problem description, we apply L5.0PIM to redesign the AMS with the aim of resolving the identified issues. First, we select the relevant Generalized EPs (GEPs), identified in the previous chapter, that align with the identified challenges. These parameters are then specified to the AMS context. Additionally, we map each Specific EP (SEP) to its corresponding parameter in the TRIZ Contradiction Matrix (CM) to facilitate systematic problem-solving.

Table 15 presents the SEPs for the identified problems in AMS, along with their corresponding parameters from the TRIZ CM.

Table 15: Mapping of SEPs to TRIZ CM Parameters

GEPs	SEPs for AMS	TRIZ Parameters for GEP	Selected Parameter for SEP
GEP5- Quality and Error Management	SEP1- Part Quality	Loss of Substance (23); Reliability (27); Accuracy of Measurement (28); Accuracy of Manufacturing (29); Factor Harmful to the Object (30); Induced Adverse Factors (31); Ease of Realization (32)	Loss of Substance (23) Relevant because part quality is affected by material removal, wear, or excessive post-processing.
GEP1- Cycle time	SEP2- Impression Time	Duration of action of the mobile object (15); Loss of Information (24); Waste of time (25); Manufacturing Accuracy (29); Ease of use (33); Product complexity (36)	Waste of Time (25) The most directly relevant as the goal is to reduce unnecessary delays in the printing process
GEP3- Environmental Impact	SEP3- Material Usage	Energy Used by the Mobile Object (19); Energy Loss (22); Loss of Substance (23); Loss of Information (24); Quantity of Substance (26); Factor Harmful to the Object (30); Ease of Realization (32)	Quantity of Substance (26) The most directly relevant as it focuses on minimizing the amount of material used in production while maintaining functionality.
GEP6- Complexity	SEP4- Post-Processing Complexity	Volume of the Moving/Static Object (07/08); Shape (12); Object Stability (13); Ease of Realization (32); Complexity of Pilotage (37); Product Complexity (36)	Ease of Realization (32) Most directly relevant because the goal is to simplify the entire post-processing phase by improving manufacturability.

As mentioned earlier, to design more performant AMS, we specifically focus on the three Lean 5.0 FRs: 1) FR11 "Design for Sustainable Pull Production"; 2) FR15 "Design for Sustainable Rapid Changeover" and 3) FR16 "Design for Sustainable Minimal Tool Use". In the following section, we customize these FRs within the context of AMS, applying the same logic as the Axiomatic model. The goal is to identify the FRs, Design Parameters (DPs), and Process variables (PVs), which form the generalized elements of L5.0PIM. These elements will then be specified to address the specific problem in this case study.

2.2 Action Parameters, Separation Principles and Generalized Solution Concepts

In the context of designing a Lean 5.0 AMS, Table 16 illustrates the customization of FR11 "Design for Sustainable Pull Production"; FR15 "Design for Sustainable Rapid Changeover" and FR16 "Design for Sustainable Minimal Tool Use", into three FRs relevant to AMS. These are paired with their DPs, which represent the Generalized Action Parameters (GAPs) in the L5.0PIM methodology, and the corresponding PVs, which reflect the Generalized Solution Concepts (GSCs) associated to the GAPs. Based on our analysis of the AM process, we specify the APs (SAPs) relevant to the challenges we aim to address. Additionally, with expert input, we identify the relevant separation principles and the corresponding GSCs for each SAP. These GSCs provide a framework that can be adjusted to address the Technical Contradictions (TCs) that will be identified later.

Table 16: Customization of Lean 5.0 FRs for AMS and Specification of APs and GSCs

Generalized Lean 5.0 FRs	Lean 5.0 FRs for AMS	DPs- GAPs	PVs- GSCs for GAPs	SAPs	Seperation Principles and GSCs for SAPs
FR11 "Design for Sustainable Pull Production"	FR11 "Minimize Print Time While Maintaining Quality"	DP11 "Reduce the Material Extrusion Time": Adjust the material distribution and select specific materials in targeted areas to achieve the required quality, while reducing the amount of material used and the time spent printing.	PV11 "External Material Application": Use of alternative procedures, such as external material extrusion, that require less time than the material used in the printing process.	SAP 1- Variable Fill Rate	**Separation in Space:** A reinforcing material can be extruded into specific target areas to enhance rigidity without affecting other regions of the print. **GSC1 "Targeted External Material Extrusion":** Integrate a precise dispensing system capable of extruding a reinforcing material, such as resin or other structural compounds, into target areas to enhance rigidity while reducing print time.
FR16 "Design for Sustainable Minimal Tool Use"	FR16 "Avoid Non-Value-Added Operations"	DP16 "Avoid Excessive Support": Minimizing the amount of support material required during the printing process to eliminate the need for post-processing tools to remove supports.	PV16 "External Support": Use of externally placed structural elements, during the AM process to ensure the deposition of the polymer filament on a	SAP 2- Support Structures	**Separtion in Time:** Plate supports structures can be temporarily added during printing to maintain structural integrity and can be removed and reused later. **GSC2 "Placement of Reusable Supports":** Integrate a solution that can accurately place plate supports into designated areas during the AM process,

			flat structure. The absence of this part could cause the structure to collapse.		guided by real-time instructions from CAD and slicer software.
FR15 “Design for Sustainable Rapid Changeover”	FR15 “Rapid Configuration”	DP15 “Insert External Parts”: Integrate pre-manufactured or alternative material parts during printing to reduce post-processing reconfiguration.	PV15 “External Part Insertion Mechanism”: Involve the precise insertion of external parts into the printed part during the printing process.	SAP 3- Incorporate Inserts	**Separation in Condition:** The external components can be inserted based on specific conditions or needs within the print, such as the location and material requirements, allowing for precise integration at the right moment. **GSC3 “Autonomous Integration of External Components”:** Integrate a solution that automates the external part insertion process by autonomously handling and integrating pre-manufactured components into the printed part.

Based on the elements identified previously, the following section presents the next step, which involves filling the matrix and formulating contradictions.

2.3 Filling the Matrix and Formulating Contradictions

In this section, we present the L5.0PIM for AMS, with a primary focus on integrating FR11 “Design for Sustainable Pull Production”; FR15 “Design for Sustainable Rapid Changeover” and FR16 “Design for Sustainable Minimal Tool Use”, to improve the current AMS by combining and integrating the FRs of Lean tools (JIT, SMED and 5S) with sustainability principle. L5.0PIM consists of two matrices: the SAPs/SAPs Matrix and the SAPs/SEPs Matrix. Based on our analysis of the AMS and expert input, we populate these matrices by evaluating the impact of each SAP on other SAPs and its effects on SEPs. Figure 34 displays the completed matrices.

							SAP \ Objective			Specific EP (SEP)			
										Max	Min	Min	Min
Lean Tool-Lean 5.0 FR	Lean 5.0 FR for AMS	Generalized AP (GAP)	GSC for GAP	Specific AP (SAP)	Separation Principles and GSC for SAP	Opposite values for SAP	SAP 1	SAP2	SAP3	SEP1 Part Quality	SEP2 Impression Time	SEP3 Material Usage	SEP4 Post-Processing Complexity
JIT- FR11 "Design for Sustainable Pull Production"	Minimize Print Time While Maintaining Quality	Reduce the Material Extrusion Time	External Material Application	SAP 1 Variable Fill Rate	Separation in Space "Targeted External Material Extrusion"	V=Max		-1	-1	-1	-1	-1	0
						$\bar{V}$=Min				+1	+1	+1	0
5S- FR16 "Design for Sustainable Minimal Tool Use"	Avoid Non-Value-Added Operations	Avoid Excessive Support	External Support	SAP 2 Support Structures	Separation in Time "Placement of Reusable Supports"	V=Max	+1		-1	+1	+1	+1	+1
						$\bar{V}$=Min				-1	-1	-1	-1
SMED-FR15 "Design for Sustainable Rapid Changeover"	Rapid Configuration	Insert External Parts	External Part Insertion Mechanism	SAP 3 Incorporate Inserts	Separation in Condition "Autonomous Integration of External Components"	V=After Printing	+1	+1		-1	-1	+1	+1
						$\bar{V}$= During Printing				+1	+1	-1	-1
Similar Parameters of the TRIZ Contradiction Matrix										23	25	26	32

Figure 34: L5.0PIM for AMS

The relationship between SAPs indicates that the integration of one SAP can either support or hinder the integration of another. The significance of this matrix lies in the fact that, when SAPs share the same objective, the integration of one parameter can help achieve the objective of the other, potentially resolving a contradiction and fulfilling the goals of both SAPs. In the following, we present an explanation of the impact values placed in the SAPs/SAPs matrix.

- Variable Fill Rate → Support Structures (-1): Adding voids (empty spaces) in the structure reduces the need for support structures, as less material is used, and certain parts can be self-supporting.
- Variable Fill Rate → Incorporate Inserts (-1): Excessive voids can make the incorporation of inserts more difficult, as they may not be well anchored or could lack structural support.
- Support Structures → Variable Fill Rate (+1): The more support structures exists, the easier it becomes to incorporate voids without compromising the stability of the print.
- Support Structures → Incorporate Inserts (-1): Excessive use of support structures can complicate the incorporation of inserts, as the supports may need to be removed.
- Incorporate Inserts → Variable Fill Rate (+1): Proper incorporation of inserts may require pre-designed voids in the structure to accommodate them.
- Incorporate Inserts → Support Structures (+1): The addition of inserts may require extra support structures to prevent the insertion area from collapsing during printing.

In the following sections, we present an explanation of the impact values placed in SAPs/SEPs matrix, along with the formulation and explanation of the TCs deduced from the matrix.

2.3.1 First Contradiction related to SAP1: Variable Fill Rate

Based on the L5.0PIM and an analysis of the current AMS, a TC between three conflicting criteria is deduced: Part quality, material consumption, and impression time. The first partial solution involved incorporating deltas (or voids) into the part design to reduce impression time. However, this can negatively impact the part's strength and stability. These voids, while reducing material usage, may lead to areas with non-uniform material distribution, creating weak points that compromise overall structural integrity, especially when the part is subjected to load or stress. This trade-off between reduced material usage and diminished rigidity is a critical consideration in AMS.

On the other hand, the second partial solution involves avoiding voids and filling the entire volume with material, which enhances structural integrity, ensuring the part is more durable and capable of withstanding stress. However, this approach often results in longer print times and increased material consumption, as more material must be deposited throughout the part. Therefore, finding a solution that balances the need for rigidity, material efficiency, and printing time is essential. These parameters must be applied to the areas of mechanical stress on the prosthesis, as shown in Figure 35.

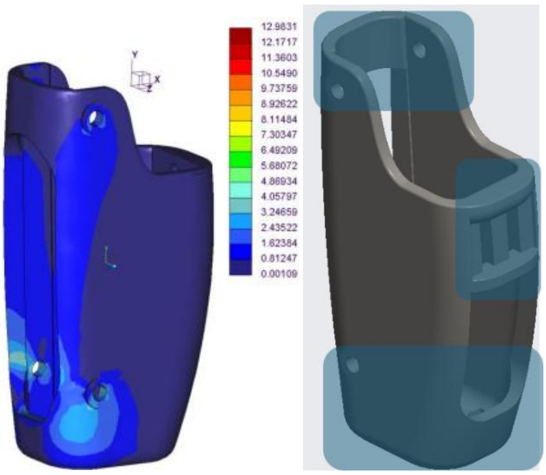

Figure 35: Areas of Mechanical Stress on the Prosthesis (Finite Element Analysis)

The contradiction system presented in this first problem is shown in Figure 36.

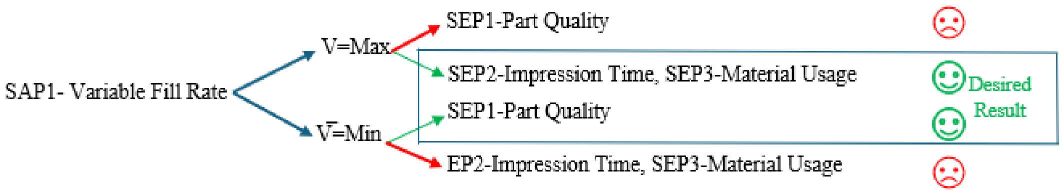

Figure 36: Contradiction System related to Variable Fill Rate

2.3.2 Second Contradiction related to SAP2: Support Structures

Another significant issue in the printing process involves the need for additional support structures during production to prevent material loss and maintain structural integrity. This is evident in the design of the rectangular assembly window of the prosthesis, as shown in Figure 37. Support structures are often added during printing to prevent deformation or collapse and maintain part quality. However, they not only increase material usage and production time but also add complexity to post-processing, as they must be carefully removed to ensure the final product meets the required specifications and to maintain the part quality.

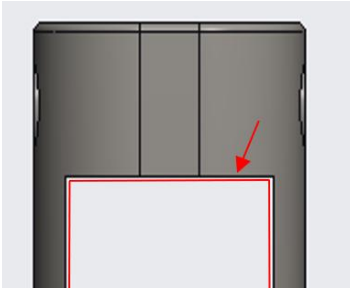

Figure 37: Assembly Window of the Prosthesis Requiring Support During Printing

The contradiction system presented in this second problem is shown in Figure 38.

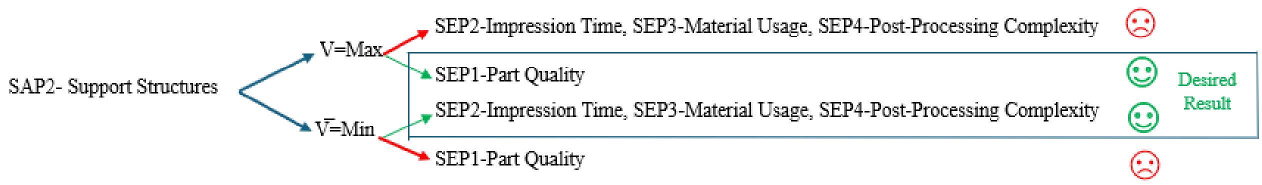

Figure 38: Contradiction System related to Support Structures

2.3.3 Third Contradiction related to SAP3: Incorporate Inserts

Another significant issue deduced in the impression process of the prosthesis and other similar products is the post-production incorporation of inserts, which can adversely affect the overall quality of the part. This process typically requires manual intervention after printing is complete, involving drilling or other modifications that can introduce inaccuracies or compromise the structural integrity of the prosthesis. This removal of material creates waste, as the excess material is discarded during the process. Additionally, the additional handling increases the risk of defects such as misalignment, stress fractures, or uneven surfaces around the insert points. Moreover, this approach often results in increased production time and inconsistency between parts, as the manual process is prone to variability. Addressing this problem requires an integrated solution during the printing phase to ensure that inserts are precisely and securely embedded without compromising the part's quality. This solution could streamline production by reducing time and labor costs while maintaining the quality of the parts.

The contradiction system presented in this third problem is shown in Figure 39.

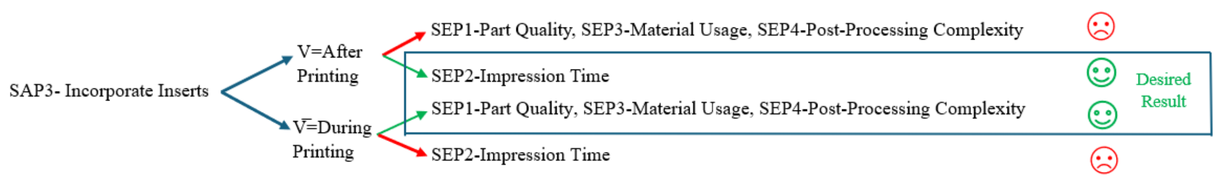

Figure 39: Contradiction System related to the Incorporation of Inserts

In the following section, we proceed with resolving the identified contradictions. This resolution follows our approach to simultaneously addressing both technical and physical contradictions.

2.4 Resolving Contradictions

The problem-solving process begins with identifying the corresponding parameters from the TRIZ CM for the SEPs. Then, by analyzing their intersections in the CM, we determine the inventive principles that can resolve these contradictions. These principles are then classified according to their corresponding separation principles, following the categorization presented in Table 11 in the previous chapter. The inventive principles classified as "Depends on context" were not included in the classification proposed by (Hipple 2012). However, they are analyzed based on the nature of the problem and expert judgment to determine which separation principle they can be attributed to. Table 17 presents the inventive principles that can resolve the identified TCs in the AMS, along with their classification into separation principles.

Table 17: Inventive Principles and their Corresponding Separation Principles

SAPs	Technical Contradictions	Corresponding Parameter from TRIZ CM	Inventive principles	Corresponding Separation principles
SAP1-Variable Fill Rate	TC1- SEP1-Part Quality VS SEP2-Impression Time	Loss of Substance (23) VS Waste of Time (25)	15- Dynamics; 18- Mechanical vibration; 35- Parameter change; 10- Prior action	Separation in Space/Time: 15; 18; 10 Separation in condition: 35
	TC2- SEP1-Part Quality VS SEP3-Material Usage	Loss of Substance (23) VS Quantity of Substance (26)	6- Universality; 3-Local quality; 10- Prior action; 24- Intermediary	Separation in Space/Time: 10 Separation between parts and whole: 6 Depends on context: 3; 24
SAP2-Support Structures	TC1- SEP1-Part Quality VS SEP2-Impression Time	Loss of Substance (23) VS Waste of Time (25)	15- Dynamics; 18- Mechanical vibration; 35- Parameter change; 10- Prior action	Separation in Space/Time: 15; 18; 10 Separation in condition: 35
	TC2- SEP1-Part Quality VS SEP3-Material Usage	Loss of Substance (23) VS Quantity of Substance (26)	6- Universality; 3-Local quality; 10- Prior action; 24- Intermediary	Separation in Space/Time: 10 Separation between parts and whole: 6 Depends on context: 3; 24
	TC3- SEP1-Part Quality VS SEP4-Post-Processing Complexity	Loss of Substance (23) VS Ease of Realization (32)	15- Dynamics; 34- Discarding and recovering; 33- Homogeneity	Separation in Space/Time: 15; 34 Depends on context: 33
SAP3-Incorporate Inserts	TC1- SEP1-Part Quality VS SEP2-Impression Time	Loss of Substance (23) VS Waste of Time (25)	15- Dynamics; 18- Mechanical vibration; 35- Parameter change; 10- Prior action	Separation in Space/Time: 15; 18; 10 Separation in condition: 35

	TC4- SEP3-Material Usage VS SEP2-Impression Time	Quantity of Substance (26) VS Waste of Time (25)	35- Parameter change; 38- Accelerate oxidation; -18- Mechanical vibration; 16- Partial or Excessive action	Separation in Condition: 35; 38 Separation in Space/ Time: 18; 16
	TC5- SEP4-Post-Processing Complexity VS SEP2-Impression Time	Ease of Realization (32) VS Waste of Time (25)	35- Parameter change; 28- Replace mechanical system; 34- Discarding and recovering; 4- Asymmetry	Separation in Condition: 35; 28 Separation in Time: 34 Depends on context: 4

Regarding the three identified GSCs for GAPs: PV11 "External Material Application", PV16 "External Support", and PV15 "External Part Insertion Mechanism", we note that the system require external interventions beyond the capabilities of the existing AMS. To address the detected issues, integrating additional equipment with the necessary functionalities provides a viable solution, with the potential for these features to be incorporated into future AMS designs. This integration aims to fulfill a proposed set of design guidelines, specifically tailored to enhance the AMS by addressing its current limitations while optimizing its performance and adaptability. In the following, we provide a detailed explanation of the solution implemented for each identified problem.

It is important to recall that the resolution process is based on two key elements: The inventive principles for resolving TCs and GSCs derived from separation principles for SAPs. In the following sections, we select the appropriate inventive principles and explore solutions to resolve the contradictions based on the GSCs identified for each SAP.

2.4.1 Resolving the Contradiction System related to Variable Fill Rate

The aim of this solution is to fulfill FR11 "Design for Sustainable Pull Production" by reducing both time and material waste. This solution is focused on combining JIT and sustainability principles to optimize production process and reduce inefficiencies.

The inventive principle selected to resolve the contradiction system related to Variable Fill Rate is Principle 3: "Local Quality". The targeted extrusion of reinforcing material ensures that the local quality of the part is enhanced where needed (increasing rigidity in specific regions), while other parts of the print maintain their original material properties and flexibility.

Based on the "Local Quality" inventive principle for resolving the TCs and the proposed GSC1 for SAP1 "Targeted External Material Extrusion", derived from the Separation in Space principle, we explore a solution to resolve the first contradiction system.

A potential solution to balance high part rigidity and quality with reduced printing time and to satisfy DP11 "Reduce the Material Extrusion Time", involves incorporating voids into the part design integrating GSC1 "Targeted External Material Extrusion" to fill these voids during the printing process. As the part is printed, voids are intentionally left unfilled, reducing material usage and print time. To realize the external material extrusion, we propose integrating a Collaborative Robot (Cobot) equipped with an extrusion system.

Once the voids are printed, the Cobot, equipped with a syringe-like dispensing tool, intervenes to extrude a resin material into these voids, effectively reinforcing the structure without compromising the overall design. This resin extrusion not only enhances local rigidity in the required areas but is also more cost-effective than the primary printing material, helping to reduce overall production costs. Once the voids are filled, the printing process proceeds, ensuring efficient printing while maintaining the necessary strength and rigidity in critical areas, thereby optimizing material usage, printing time and production costs. This solution can resolve both TC1 and TC2, as it maintains part quality, does not increase the impression time of the part, and reduces material usage.

Figure 40 shows the syringe equipped on the Cobot to be used during the prosthesis printing process.

Figure 40: Syringe Equipped on the Cobot during Prosthesis Printing

2.4.2 Resolving the Contradiction System related to Support Structures

The aim of this solution is to fulfill FR16, "Design for Sustainable Minimal Tool Use" by reducing the need to apply 5S and eliminating the tools used in the post-processing structure, thereby reducing the need to organize these tools and eliminating the time spent searching for tools. This solution combines 5S and sustainability to reduce material waste associated with removed structures, minimize post-processing complexity, and decrease the use of tools that can be eliminated in the system design.

The inventive principle selected to resolve the contradiction system related to Support Structures is Principle 15: "Dynamics". The reusable supports are designed to adapt to the changing conditions during the printing process. Supports are only added when necessary and removed or reused at later stages, adjusting dynamically to the needs of the print. This adaptability ensures the best use of material and resources, enhancing overall efficiency.

Based on the "Dynamics" inventive principle for resolving the TC and the proposed GSC2 for SAP2 "Placement of Reusable Supports", derived from the Separation in Time principle, we explore a solution to resolve the second contradiction system.

To fulfill DP16, "Avoid Excessive Support", we need to integrate an external system capable of applying GSC2, "Placement of Reusable Supports". To achieve this, we propose integrating a Cobot equipped with a metal plate that replaces the role of material support during printing.

The Cobot's capabilities is utilized to implement this solution: The insertion of a metal plate during critical moments in the printing process when additional support is required. This metal plate is temporarily acts as a support structure, enabling the seamless continuation of the printing process without the need for traditional, material-intensive support structures.

This approach brings multiple advantages. First, it significantly reduces manufacturing time by eliminating the need to print and later remove conventional support structures. Moreover, the reusability of the metal plate further enhances cost-efficiency, as it can be recovered, cleaned, and repurposed for subsequent prints.

By minimizing the dependency on printed supports, the process reduces raw material consumption, leading to cost savings and more sustainable manufacturing practices. Additionally, the reduction in printing time is substantial, using a Cobot to implement this method can shorten production by up to 3 hours per unit. This time savings, when scaled across multiple production runs, represents a transformative improvement in throughput and overall efficiency.

Furthermore, this solution maintains high print quality, as the metal plate provides robust and stable support precisely where it is needed, preventing deformation or material loss during the printing process. The Cobot's involvement ensures consistent and repeatable results, enhancing reliability and reducing the likelihood of errors that could arise from manual interventions.

2.4.3 Resolving the Contradiction System related to Inserts Incorporation

The aim of this solution is to fulfill FR15 "Design for Sustainable Rapid Changeover" by reducing configuration variability related to each part and minimizing the need for tool or system changes responsible for insert incorporation during the post-processing phase. This solution combines SMED and sustainability to reduce material waste associated with material removal, streamline post-processing complexity, and shorten configuration time.

The inventive principle selected to resolve the contradiction system related to inserts incorporation is "Principle 28": "Replace Mechanical System". The use of automated integration systems to insert external components replaces the traditional manual insertion process. This automation eliminates post-impression's human intervention, improving efficiency and precision.

Based on the "Replace Mechanical System" inventive principle for resolving the TCs and the proposed GSC3 for SAP3 "Autonomous Integration of External Components", derived from the Separation in Condition principle, we explore a solution to resolve the third contradiction system.

To address the issue of post-production incorporation of inserts and the impact on part quality and to satisfy DP15 "Insert External Parts", we propose a solution that involves incorporating the inserts directly into the part during the 3D printing process, integrating GSC3 "Autonomous Integration of External Components".

Instead of waiting until after the print is completed to manually incorporate the inserts, we propose that the Cobot precisely places the inserts in real-time as the part is built layer by layer. The Cobot uses a specialized end effector, precise grippers, or specialized tools to ensure that the inserts are accurately positioned and securely integrated into the part without disrupting the print. The Cobot can pick, position, and insert components such as metal inserts, fasteners, or other external elements into the print during the printing process. Equipped with sensors and vision systems, the Cobot ensures accurate placement and alignment, seamlessly integrating these parts without interrupting the ongoing print.

This solution eliminates the need for additional drilling or manual insertion, which can cause misalignment or damage to the part, ultimately improving the quality and integrity of the final product. The automation of this process also saves significant time by eliminating the manual incorporation of inserts and removing post-processing steps, thereby reducing post-processing complexity. By embedding the inserts during the printing process, there is less material waste caused by removal during drilling or other modifications. The excess material is discarded during the printing process, resulting in a more streamlined workflow. This solution enhances manufacturing efficiency, reduces the risk of errors, and ensures that the inserts are consistently embedded in the correct locations, improving both the speed and quality of production.

Figure 41 presents a comparison of the prosthesis before and after the implementation of the proposed solution. Prior to implementation, the inserts are not incorporated and require manual intervention, whereas after implementation, the inserts are automatically integrated during the printing process.

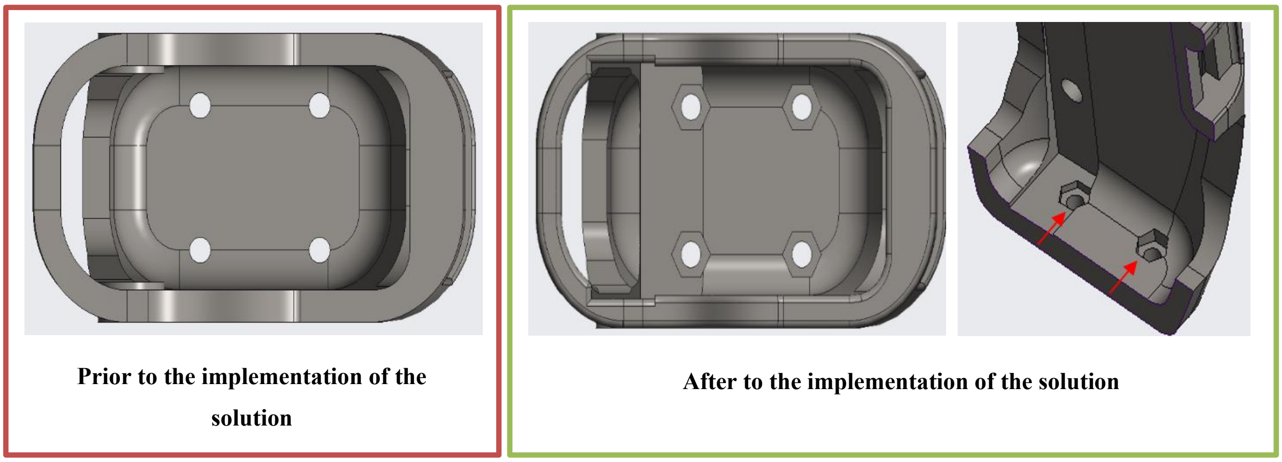

Figure 41: Incorporation of Inserts into the Prosthesis

Integrating these proposed solutions leads to removing humans from dangerous and repetitive tasks, such as the manual extrusion of external material. This also reduces the likelihood of errors, including the removal of supports and the incorporation of inserts after the printing process. These solutions not only help eliminate wastes and optimize costs and resources but also ensure sustainable production that aligns with I5.0 requirements. This application aims to support designers in fulfilling specified Lean requirements by integrating technologies and practices from the I5.0 context, specifically tailored to AMS.

This application has been focused on implementing FR11 “Design for Sustainable Pull Production”; FR15 “Design for Sustainable Rapid Changeover” and FR16 “Design for Sustainable Minimal Tool Use”, within AMS. The integration of other FRs from our Lean 5.0 generalized Axiomatic model can be explored in future research. Figure 42 shows the 3D printer and the Cobot into which the solutions are integrated and used in the prosthesis printing process.

Figure 42: 3D Printer and Cobot Used in Prosthesis Printing Process

Conclusion

In this chapter, we presented a case study applying the L5.0PIM methodology to enhance the performance of the current AMS. We identified various contradictions and proposed inventive solutions to resolve them. These solutions are implemented through the integration of Cobot, which fulfill the GSCs that support Lean requirements by reducing time waste, material waste, improving part quality and avoid post-processing complexity, while also supporting the sustainability principle of I5.0. These solutions are considered for application in the FABLAB of the CSIP team in INSA Strasbourg.

General Conclusion

This research represents one of the first initiatives to introduce the Lean 5.0 concept and proactively integrate its requirements from the design phase of manufacturing systems. The aim is to integrate Lean and Industry 5.0 (I5.0) principles, specifically sustainability, resilience, and human-centricity, to design systems with the desired performance from the beginning, thereby eliminating the need for Lean interventions in future system designs. We proposed a Lean 5.0 framework that integrates the added value of Lean tools from the design phase, overcoming the constraints and challenges of their implementation in existing systems while addressing the limitations of Lean 4.0 by aligning this integration with I5.0 principles.

Our research explore the potential of combining routine and inventive methods to clarify key elements and address the complexities of integrating multiple Lean and I5.0 requirements within an expanded general context. The primary objective is to develop a methodology that facilitates the resolution of multiple independent or interrelated problems within the context of the proactive Lean 5.0 integration. This methodology seeks to provide standard guidelines for designers to enhance their designs by integrating Lean requirements into an I5.0 context, while effectively resolving any contradictions that emerge from this integration.

1. Contributions

The first contribution related to our research was analyzing the integration of Lean 4.0 from the design phase through an empirical study, using exploratory and confirmatory factor analysis to evaluate the impact of this integration on the performance of manufacturing systems (Gdoura et al. 2024a). As the research progressed, we identified several limitations in the Lean 4.0 framework that were contradictory to the emerging I5.0 concept. These limitations prompted us to develop the Lean 5.0 concept, which combines Lean tool requirements with I5.0 principles.

In this thesis, we have identified eight key gaps related to the integration of Lean and I5.0 principles into the design of manufacturing systems. Research has primarily focused on improving the design process itself rather than enhancing the designed system. There is an ambiguous understanding of Lean requirements and a lack of guidelines for their integration. Existing studies on I5.0 integration tend to address its principles separately, without a holistic approach. Additionally, there is a lack of empirical studies evaluating Lean 4.0 tools from the design phase, as well as limited analysis of the relationship between Lean tools and I5.0 principles. Notably, there is a Moreover, few researchers have addressed the concept of Lean 5.0, including the analysis of convergences between Lean tools and I5.0 principles.

Given the lack of studies analyzing the synergy between Lean and I5.0 principles, we took a step back to examine how Lean have already addressed sustainability, resilience, and human-centricity, key aspects of I5.0, even before the concept emerged. This analysis allows us to understand how Lean inherently incorporates these principles, independent of the technological advancements emphasized in I5.0.

There is also a noted absence of guidelines and methodologies for formulating and integrating Lean 5.0 tool requirements during the design phase of manufacturing systems, nor an Axiomatic model that aligns Lean tools with I5.0 principles. Most existing research has primarily focused on applying Lean principles to established systems, with an emphasis on the organizational, strategic, and managerial aspects of Lean production. Additionally, articles exploring the integration of AD with I4.0 and I5.0 have largely highlighted the importance of using AD to design complex systems that merge both paradigms, although practical applications remain scarce. Finally, there is an lack of methodologies leveraging TRIZ theory for identifying and resolving contradictions arising from the integration of multiple Lean functionalities during the design phase. All these gaps were addressed to develop a structured approach for designing an inventive Lean 5.0 manufacturing systems that effectively combine Lean requirements and I5.0 principles while minimizing or avoiding the need to apply Lean tools during the operational phase of future systems.

From a methodological perspective, our study proposes a methodology consisting of three major phases. The first phase involves extracting from the literature a set of Lean requirements and their corresponding parameters within an I5.0 context to fulfill multiple performance criteria identified through a review of 34 DfX methodologies. In this phase, we provided guidelines consisting of a list of more than 100 requirements and their corresponding parameters for researchers and practitioners, illustrating how Lean tools can be adapted and oriented during the design phase to more effectively satisfy I5.0 principles.

The second phase involves proposing a new generalized Lean 5.0 Axiomatic model that emphasizes the proactive integration of Lean requirements in an I5.0 context into the design of manufacturing systems. By integrating the technological advancements of I5.0 with traditional Lean concepts that preserve its core values, we developed a Lean 5.0 proactive-based model, blending digital innovations with human-centric, sustainable, and resilient manufacturing practices. This model comprises three main facets: "Design a Sustainable Lean Manufacturing System", "Design a Resilient Lean Manufacturing System" and "Design a Human-Centric Lean Manufacturing System". It serves as a guideline for aligning each of the fundamental principles of I5.0 with eight Lean Functional Requirements (FRs), derived from an analysis of the limitations of Lean tool applications in existing systems. Additionally, the proposed model identifies the design parameters and process variables to be considered in this integration.

Our research is original in proposing a novel roadmap using AD for the comprehensive design of Lean 5.0 manufacturing systems. The proposed roadmap outlines the decomposition of fundamental design objectives related to Lean and I5.0 concepts into supporting design objectives. Additionally, the absence of prior work attempting to design systems that integrate both Lean and I5.0 principles using AD highlights the significance of this study. It serves as a fundamental proposal that can be further developed to provide domain-specific details for various industries.

Regarding our aim to integrate multiple Lean 5.0 requirements, attempting to incorporate their corresponding parameters derived from our Lean 5.0 Axiomatic model can generate contradictions. Leveraging the complementarity between the TRIZ and AD methods, this brings us to the third major phase of our thesis. This part involves proposing a new methodology named the "Lean 5.0 Parameter Integration

Matrix (L5.0PIM)" which aims to analyze and resolve contradictions arising from the integration of multiple Lean 5.0 parameters during the design phase, preventing potential issues in the future system being designed.

Our proposed approach enables the simultaneous resolution of technical and physical contradictions, ensuring that both are addressed within a single design step. It does so by proposing Generalized Solution Concepts (GSCs) for resolving physical contradictions based on separation principles, followed by identifying and resolving the technical contradictions within the context of GSCs.

L5.0PIM is composed of Generalized Action Parameters (GAPs) derived from the Axiomatic model, along with the Generalized Evaluation Parameters (GEPs) that categorize more than 100 parameters corresponding to Lean requirements extracted from the literature.

We conducted a case study to apply the L5.0PIM methodology to improve the performance of the current AMS in prototyping a Handiski Knee Prosthesis, with a specific focus on FR11 "Design for Sustainable Pull Production"; FR15 "Design for Sustainable Rapid Changeover" and FR16 "Design for Sustainable Minimal Tool Use". We identified the different challenges and the specific parameters related to them, formulating and resolving contradictions by proposing inventive solutions based on the integration of a Cobot. The results indicate a reduction in printing time and material consumption, along with an improvement in part quality, the elimination of human involvement in hazardous and repetitive tasks and the reduction of post-processing complexity.

2. Limitations

Our study acknowledges certain limitations and simultaneously outlines research perspectives.

The first limitation is that the Design for Lean 5.0 methodology introduces Lean 5.0 requirements in addition to the technical requirements specified by the client, which may increase the designer's workload. At present, the impact of this additional workload on the designer's productivity and motivation has not yet been evaluated.

The second limitation is that Lean 5.0 requirements are presented in a general way, lacking specific guidance to offer the designer the most optimal solutions. The process of tailoring these requirements to a particular problem and generating solution concepts depends on the methods and tools used by the designer, which in turn reflect their knowledge and skills.

The third limitation is that the validation of the Lean 5.0 Axiomatic model is based on a single case study. Conducting broader empirical testing across multiple case studies would provide a more comprehensive evaluation of its practical applicability in different manufacturing environments.

The fourth limitation is that the complexity of integrating both Lean and I5.0 principles may pose challenges in system implementation, requiring careful consideration of how technologies, human factors, and sustainability can be effectively balanced. These aspects should be further explored in future research to refine and fully develop detailed implementation scenarios for Lean 5.0 requirements.

The fifth limitation of the L5.0PIM methodology is the inclusion of manual tasks, which can impose additional effort on the designer's workload. These tasks include identifying contradictions, mapping relevant parameters, and determining suitable solutions, which is a process that can be both time-consuming and prone to human error.

3. Perspectives

Our Design for Lean 5.0 methodology is the first initiative to combine and integrate Lean and I5.0 requirements in the design of manufacturing systems, as well as to formulate and resolve the contradictions that may arise from this integration. However, it requires further development to overcome its current limitations.

To address the challenges posed by manual tasks in L5.0PIM, future research will focus on integrating Artificial Intelligence (AI) into the methodology to automate these tasks. Using natural language processing (NLP), the system will scan patents, technical documents, and case studies to extract relevant solutions and map them to identified contradictions. Machine learning algorithms will predict optimal solutions based on historical data, best practices, and domain-specific knowledge. Future developments will focus on:

1. Automated identification and specification of generalized APs, based on the designer's problem definition.
2. Automatic completion of the matrix, ensuring a structured and efficient approach to contradiction analysis.
3. AI-driven solution generation, leveraging a patent database and documented case studies to provide optimized, data-informed recommendations.

This initiative represents a key future direction of our research, with the goal of significantly enhancing the efficiency, scalability, and intelligence of the L5.0PIM framework. By integrating automation and AI-driven methodologies, we aim to transform L5.0PIM into a powerful, data-informed decision-making tool, capable of handling complex design contradictions with greater precision and speed. The insights gained from this process will be instrumental in building a robust AI-based model capable of autonomously generating solution concepts in the future, further enhancing the efficiency and accuracy of the L5.0PIM framework.

The case study presented in this thesis represents an initial effort to specify the generalized parameters of L5.0PIM for AMS. Future research will further explore the adaptation of the remaining parameters and propose an AMS-specific L5.0PIM.

Given the challenges faced in adapting parameters to AMS, the L5.0PIM could be applied more effectively to a broader manufacturing system that includes a wider range of process parameters. This perspective is a part of our long-term vision to develop a tool for the L5.0PIM that offers varying levels of parameter complexity based on a company's maturity in Lean and I5.0 principles. This perspective is inspired by the CES EduPack software (Ashby and Cebon 2007). CES EduPack is designed to enhance understanding of materials and their selection in engineering and design contexts, it features a comprehensive materials database that provides detailed information on properties such as mechanical, thermal, electrical, and environmental characteristics. In our case, L5.0PIM focuses on improving manufacturing system performance by starting with a foundational set of parameters that are less complex, allowing for greater adaptability for designers. As users become more proficient, we can introduce more complex matrices with additional parameters to further enhance the tool's capabilities.

Another potential direction for future work is the incorporation of sensitivity analysis, which could offer valuable insights to validate the independence of the solutions in the Lean 5.0 Axiomatic model and confirm their effectiveness across various manufacturing contexts. This approach would enable further optimization and refinement of Lean 5.0 systems.

References

Abdellatif, M., Chibane, H., Dubois, S., & De Guio, R. (2024). Integrating the generalized table of parameters and contextual database in an inventive design method to extract problems to be solved. *FME Transactions*, *52*(2), 246-256.

Abdellatif, M., Chibane, H., Dubois, S., De Guio, R., & Roland, T. (2023). Method to build a generalized table of parameters in engineering design of technical systems: lattice structure as a case study. *FME Transactions*, *51*(4), 480-496.

Abdullah, A., Saraswat, S., & Talib, F. (2023). Impact of smart, green, resilient, and lean manufacturing system on SMEs' performance: A Data Envelopment Analysis (DEA) approach. *Sustainability*, *15*(2), 1379.

Aggarwal, A., Kumar, S., & Sikor, T. (2005). TOYOTrizzed: How the celebrated TOYOTA Production System is a TRIZ derivative. *The TRIZ Journal*.

Agote-Garrido, A., Martín-Gómez, A. M., & Lama-Ruiz, J. R. (2023). Redesign of Manufacturing Workstation with Value Sensitive Design and Axiomatic Design to Incorporate Values of Industry 5.0. *Advances in Science and Technology*, *132*, 250-259.

Ahuja, I. P. S., & Khamba, J. S. (2008). Total productive maintenance: literature review and directions. *International journal of quality & reliability management*, *25*(7), 709-756.

Almeida Marodin, G., & Saurin, T. A. (2015). Managing barriers to lean production implementation: context matters. *International Journal of Production Research*, *53*(13), 3947-3962.

Al′tshuller, Genrikh Saulovich. 1999. The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity. Technical innovation center, Inc.

Alves, J., Lima, T. M., & Gaspar, P. D. (2023). Is industry 5.0 a human-centred approach? A systematic review. *Processes*, *11*(1), 193.

Anvari, A., Zulkifli, N., Sorooshian, S., & Boyerhassani, O. (2014). An integrated design methodology based on the use of group AHP-DEA approach for measuring lean tools efficiency with undesirable output. *The International Journal of Advanced Manufacturing Technology*, *70*, 2169-2186.

Arnette, A. N., Brewer, B. L., & Choal, T. (2014). Design for sustainability (DFS): the intersection of supply chain and environment. *Journal of cleaner production*, *83*, 374-390.

Ashby, M. F., Cebon, D., & Silva, A. (2007). Teaching engineering materials: the CES EduPack. *Engineering Department, Cambridge University*, 1-13.

Bajic, B., Medojevic, M., Simeunovic, N., & Rikalovic, A. (2023, October). Digital Kaizen: Opportunities and challenges in industry 5.0. In *19th Int. Sci. Conf. Ind. Syst.(IS)*.

Baptista, A. J., Peixoto, D., Ferreira, A. D., & Pereira, J. P. (2018). Lean design-for-X methodology: Integrating modular design, structural optimization and ecodesign in a machine tool case study. *Procedia CIRP*, *69*, 722-727.

Barbosa, G. F., Carvalho, J. D., & Filho, E. V. G. (2014). A proper framework for design of aircraft production system based on lean manufacturing principles focusing to automated processes. *The International Journal of Advanced Manufacturing Technology*, *72*, 1257-1273.

Bashkite, V., & Karaulova, T. (2012). Integration of Green thinking into Lean fundamentals by Theory of Inventive Problems-Solving tools. *DAAAM International, Vienna, Austria, EU*, 345-350.

Battaïa, O., Dolgui, A., Heragu, S. S., Meerkov, S. M., & Tiwari, M. K. (2018). Design for manufacturing and assembly/disassembly: joint design of products and production systems. *International Journal of Production Research*, *56*(24), 7181-7189.

Benabdellah, A. C., Benghabrit, A., Bouhaddou, I., & Benghabrit, O. (2020). Design for relevance concurrent engineering approach: integration of IATF 16949 requirements and design for X techniques. *Research in Engineering Design*, *31*, 323-351.

Benabdellah, A. C., Bouhaddou, I., Benghabrit, A., & Benghabrit, O. (2019). A systematic review of design for X techniques from 1980 to 2018: concepts, applications, and perspectives. *The International Journal of Advanced Manufacturing Technology*, *102*, 3473-3502.

Bligh, A. (2006). The overlap between TRIZ and lean. *University of Rhode Island*, 1-10.

Boumsisse, I., Benhadou, M., & Haddout, A. (2025). Optimizing Green Lean Six Sigma using Industry 5.0 Technologies. *Cleaner Waste Systems*, 100234.

Boutbagha, M., & El Abbadi, L. (2024). Heijunka-levelling customer orders: a systematic literature review. *International Journal of Production Management and Engineering*, *12*(1), 31-41.

Braglia, M., Di Paco, F., Frosolini, M., & Marrazzini, L. (2023). Quick changeover design: a new Lean methodology to support the design of machines in terms of rapid changeover capability. *Journal of Manufacturing Technology Management*, *34*(9), 84-114.

Brown, C. A., & Rauch, E. (2019). Axiomatic design for creativity, sustainability, and industry 4.0. In *MATEC Web of Conferences* (Vol. 301, p. 00016). EDP Sciences.

Browning, T. R., & Heath, R. D. (2009). Reconceptualizing the effects of lean on production costs with evidence from the F-22 program. *Journal of operations management*, *27*(1), 23-44.

Cabrera, B. R., & Li, G. J. (2014, June). A lean-TRIZ approach for improving the performance of construction projects. In *22nd annual conference of the international group for lean construction: understanding and improving project based production, IGLC* (pp. 883-894).

Ceschin, F., & Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design studies*, *47*, 118-163.

Chaple, A. P., Narkhede, B. E., Akarte, M. M., & Raut, R. (2021). Modeling the lean barriers for successful lean implementation: TISM approach. *International Journal of Lean Six Sigma*, *12*(1), 98-119.

Charter, M., & Gray, C. (2008). Remanufacturing and product design. *International Journal of Product Development*, *6*(3-4), 375-392.

Cheung, W. M., Leong, J. T., & Vichare, P. (2017). Incorporating lean thinking and life cycle assessment to reduce environmental impacts of plastic injection moulded products. *Journal of Cleaner Production*, *167*, 759-775.

Chibane, H., Dubois, S., & De Guio, R. (2021). Innovation beyond optimization: Application to cutting tool design. *Computers & Industrial Engineering*, *154*, 107139.

Chincholkar, M. M., Hermann, J. W., & Wei, Y. F. (2003, January). Applying design for production methods for improved product development. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 37017, pp. 13-22).

Choi, T. Y., Netland, T. H., Sanders, N., Sodhi, M. S., & Wagner, S. M. (2023). Just-in-time for supply chains in turbulent times. *Production and Operations Management*, *32*(7), 2331-2340.

Chowdary, B. V., Richards, M. A., & Gokool, T. (2019). An integrated approach for sustainable product design: concurrent application of DFMA, DFE and CAD/CAE principles and tools. *Latin American Journal of Management for Sustainable Development*, *4*(4), 259-275.

Ciannella, S., & Santos, L. C. (2022). Exploring the influence of lean manufacturing practices on employee social sustainability. *Social Responsibility Journal*, *18*(8), 1677-1691.

Clark, G., Kosoris, J., Hong, L. N., & Crul, M. (2009). Design for sustainability: current trends in sustainable product design and development. *Sustainability*, *1*(3), 409-424.

Cochran, D. S., & Rauch, E. (2020). Sustainable enterprise design 4.0: Addressing industry 4.0 technologies from the perspective of sustainability. *Procedia Manufacturing*, *51*, 1237-1244.

Cohen B (1998) Design for reuse. NBERWorking Papers. https:// www.nber.org/pa-pers/w16019.

Coulibaly, A., Houssin, R., & Mutel, B. (2008). Maintainability and safety indicators at design stage for mechanical products. *Computers in industry*, *59*(5), 438-449.

Coulibaly, S. (2017). The contribution of TRIZ integration with others design tools in the engineering design process. *International Journal of Innovative Research in Science, Engineering and Technology*, *6*, 684-693.

Crowe, D., & Feinberg, A. (2017). *Design for reliability*. CRC press.

Dahmani, N., Benhida, K., Belhadi, A., Kamble, S., Elfezazi, S., & Jauhar, S. K. (2021). Smart circular product design strategies towards eco-effective production systems: A lean eco-design industry 4.0 framework. *Journal of Cleaner Production*, *320*, 128847.

Das, S., & Kanchanapiboon, A. (2011). A multi-criteria model for evaluating design for manufacturability. *International Journal of Production Research*, *49*(4), 1197-1217.

Dayi, O., Afsharzadeh, A., & Mascle, C. (2016). A Lean based process planning for aircraft disassembly. *IFAC-PapersOnLine*, *49*(2), 54-59.

De Silva, N., Ranasinghe, M., & De Silva, C. R. (2012). Maintainability approach for lean maintenance. In *World Construction Conference* (pp. 100-109).

De Souza, R. O., Ferenhof, H. A., & Forcellini, F. A. (2022). Industry 4.0 and Industry 5.0 from the Lean perspective. *Int. J. Manag. Knowl. Learn*, *11*, 145-155.

Desai, A., & Mital, A. (2006). Design for maintenance: basic concepts and review of literature. *International Journal of Product Development*, *3*(1), 77-121.

Dewi, S. R., & Setiawan, B. (2013, June). 5S program to reduce change-over time on forming department (case study on CV Piranti Works temanggung). In *IOP conference series: materials science and engineering* (Vol. 46, No. 1, p. 012040). IOP Publishing.

Dillinger, F., Kagerer, M., & Reinhart, G. (2021). Concept for the development of a Lean 4.0 reference implementation strategy for manufacturing companies. *Procedia CIRP*, *104*, 330-335.

Ding, B., Ferras Hernandez, X., & Agell Jane, N. (2023). Combining lean and agile manufacturing competitive advantages through Industry 4.0 technologies: an integrative approach. *Production planning & control*, *34*(5), 442-458.

Dombrowski, U., Schmidt, S., & Schmidtchen, K. (2014). Analysis and integration of design for X approaches in lean design as basis for a lifecycle optimized product design. *Procedia CIRP*, *15*, 385-390.

Dubois, S., Rasovska, I., & De Guio, R. (2009). Interpretation of a general model for inventive problems, the generalized system of contradictions.

e Sousa, N. J. P., Navas, H. V., & Machado, V. C. (2014). Application of Lean and TRIZ Methodologies in the Maintenance Service of a Food Company. In *The 2014 International Conference on Systematic Innovation, San Jose, the USA*.

Eriksson, K. M., Olsson, A. K., & Carlsson, L. (2024). Beyond lean production practices and Industry 4.0 technologies toward the human-centric Industry 5.0. *Technological Sustainability*, *3*(3), 286-308.

Espina-Romero, L., Guerrero-Alcedo, J., Goñi Avila, N., Noroño Sánchez, J. G., Gutiérrez Hurtado, H., & Quiñones Li, A. (2023). Industry 5.0: Tracking scientific activity on the most influential industries, associated topics, and future research agenda. *Sustainability*, *15*(6), 5554.

European Commission, Directorate-General for Research and Innovation, Breque M, De Nul L, Petridis A (2021) Industry 5.0—towards a sustainable, human-centric and resilient European industry. Publications Office of the European Union. https://doi.org/10.2777/308407

Fani, V., Bucci, I., Rossi, M., & Bandinelli, R. (2024). Lean and industry 4.0 principles toward industry 5.0: a conceptual framework and empirical insights from fashion industry. *Journal of Manufacturing Technology Management*, *35*(9), 122-141.

Fonda, E., & Meneghetti, A. (2022). The human-centric SMED. *Sustainability*, *14*(1), 514.

Formentini, G., Boix Rodríguez, N., & Favi, C. (2022). Design for manufacturing and assembly methods in the product development process of mechanical products: a systematic literature review. *The International Journal of Advanced Manufacturing Technology*, *120*(7), 4307-4334.

G. Pahl, W. Beitz, J. Feldhusen, and K.-H. Grote, Engineering design: a Systematic Approach. 2007.

García-Alcaraz, J. L., Díaz Reza, J. R., Sánchez Ramírez, C., Limon Romero, J., Jimenez Macias, E., Lardies, C. J., & Rodríguez Medina, M. A. (2021). Lean manufacturing tools applied to material flow and their impact on economic sustainability. *Sustainability*, *13*(19), 10599.

García-Alcaraz, J. L., Morales Garcia, A. S., Díaz-Reza, J. R., Jimenez Macias, E., Javierre Lardies, C., & Blanco Fernandez, J. (2022). Effect of lean manufacturing tools on sustainability: the case of Mexican maquiladoras. *Environmental Science and Pollution Research*, *29*(26), 39622-39637.

García-Cutrín, J., & Rodríguez-García, C. (2024). Enhancing corporate sustainability through Just-In-Time (JIT) practices: a meta-analytic examination of financial performance outcomes. *Sustainability*, *16*(10), 4025.

Gdoura, R., Houssin, R., Chibane, H., Dhouib, D., & Coulibaly, A. (2024, October). A New TRIZ-Based Approach to Design an Innovative Production System by Integrating Lean Tools and Functionalities. In *International TRIZ Future Conference* (pp. 23-35). Cham: Springer Nature Switzerland.

Gdoura, R., Houssin, R., Coulibaly, A., & Dhouib, D. (2024a). Towards the integration of Lean 4.0 from the design phase of production systems: a new framework. *International Journal of Product Lifecycle Management*, *15*(3), 230-258.

Gdoura, R., Houssin, R., Dhouib, D., & Coulibaly, A. (2025). Design for lean 5.0: Integrating lean requirements and parameters into production systems in an industry 5.0 context. *Concurrent Engineering*, 1063293X241312094.

Gero, J. S., & Kannengiesser, U. (2004). The situated function–behaviour–structure framework. *Design studies*, *25*(4), 373-391.

Gobbo Junior, O., & Borsato, M. (2021). A method to support design for serviceability in the early stages of new product development. *International Journal of Computer Integrated Manufacturing*, *34*(1), 41-56.

Godina, R., Pimentel, C., Silva, F. J. G., & Matias, J. C. (2018). A structural literature review of the single minute exchange of die: the latest trends. *Procedia Manufacturing*, *17*, 783-790.

Goffin, K. (2000). Design for supportability: essential component of new product development. *Research-Technology Management*, *43*(2), 40-47.

Golovianko, M., Terziyan, V., Branytskyi, V., & Malyk, D. (2023). Industry 4.0 vs. Industry 5.0: Co-existence, transition, or a hybrid. *Procedia Computer Science*, *217*, 102-113.

Grosse, E. H., Sgarbossa, F., Berlin, C., & Neumann, W. P. (2023). Human-centric production and logistics system design and management: transitioning from Industry 4.0 to Industry 5.0. *International Journal of Production Research*, *61*(22), 7749-7759.

Gu, X., Jin, X., Ni, J., & Koren, Y. (2015). Manufacturing system design for resilience. *Procedia Cirp*, *36*, 135-140.

Gupta, S., & Jain, S. K. (2013). A literature review of lean manufacturing. *International journal of management science and engineering management*, *8*(4), 241-249.

Habibi Rad, M., Mojtahedi, M., & Ostwald, M. J. (2021). The integration of lean and resilience paradigms: A systematic review identifying current and future research directions. *Sustainability*, *13*(16), 8893.

Hachicha, W., Masmoudi, F., & Haddar, M. (2008). Combining axiomatic design and designed experiments for cellular manufacturing systems design framework. *International Journal of Agile Systems and Management*, *3*(3-4), 306-319.

Hafey, R. (2017). *Lean safety: Transforming your safety culture with lean management*. CRC Press.

Haik, Y., Shahin, T. M., & Sivaloganathan, S. (2011). *Engineering design process* (Vol. 287). Stamford: Cengage Learning.

Harrington, H. J. (2017). *Lean TRIZ: How to dramatically reduce product-development costs with this innovative problem-solving tool*. Productivity Press.

Hasan, R., Bernard, A., Ciccotelli, J., & Martin, P. (2003). Integrating safety into the design process: elements and concepts relative to the working situation. *Safety science*, *41*(2-3), 155-179.

Hasenkamp, T. (2010). Engineering Design for Six Sigma—a systematic approach. *Quality and Reliability Engineering International*, *26*(4), 317-324.

Hatcher, G. D., Ijomah, W. L., & Windmill, J. F. C. (2011). Design for remanufacture: a literature review and future research needs. *Journal of Cleaner Production*, *19*(17-18), 2004-2014.

Herrmann, J. W., & Chincholkar, M. M. (2001). Reducing throughput time during product design. *Journal of Manufacturing Systems*, *20*(6), 416-428.

Hines, P. (2022). Human centred lean–introducing the people value stream. *International Journal of Lean Six Sigma*, *13*(5), 961-988.

Hipple, J. (2012). The ideal result. In *The Ideal Result: What It Is and How to Achieve It* (pp. 23-32). New York, NY: Springer New York.

Hoppmann, J., Rebentisch, E., Dombrowski, U., & Zahn, T. (2011). A framework for organizing lean product development. *Engineering Management Journal*, *23*(1), 3-15.

Houshmand, M., & Jamshidnezhad, B. (2002, June). Conceptual design of lean production systems through an axiomatic approach. In *Proceedings of ICAD2002 Second International Conference on Axiomatic Design*.

Houshmand, M., & Jamshidnezhad, B. (2006). An extended model of design process of lean production systems by means of process variables. *Robotics and Computer-Integrated Manufacturing*, *22*(1), 1-16.

Houssin, R., & Coulibaly, A. (2011). An approach to solve contradiction problems for the safety integration in innovative design process. *Computers in industry*, *62*(4), 398-406.

Houssin, R., Bernard, A., Martin, P., Ris, G., & Cherrier, F. (2006). Information system based on a working situation model for a new design approach in concurrent engineering. *Journal of Engineering Design*, *17*(1), 35-54.

Hultgren, N. (2012). Guidelines and design strategies for improved product recyclability-how to increase the recyclability of consumer electronics and domestic appliances through product design.

Hüttmeir, A., De Treville, S., Van Ackere, A., Monnier, L., & Prenninger, J. (2009). Trading off between heijunka and just-in-sequence. *International journal of production economics*, *118*(2), 501-507.

Iakymenko, N., Brett, P. O., Alfnes, E., & Strandhagen, J. O. (2022). Analyzing the factors affecting engineering change implementation performance in the engineer-to-order production environment: case studies from a Norwegian shipbuilding group. *Production Planning & Control*, *33*(9-10), 957-973.

Ikovenko, S., & Bradley, J. (2004, November). TRIZ as a lean thinking tool. In *Proceedings of the TRIZ Future 4th World Conference, Florence* (pp. 3-5).

Ivanov, D. (2022). Lean resilience: AURA (Active Usage of Resilience Assets) framework for post-COVID-19 supply chain management. *The International Journal of Logistics Management*, *33*(4), 1196-1217.

Ivanov, D. (2023). The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives. *International Journal of Production Research*, *61*(5), 1683-1695.

Jackson, S. A., Gopalakrishna-Remani, V., Mishra, R., & Napier, R. (2016). Examining the impact of design for environment and the mediating effect of quality management innovation on firm performance. *International Journal of Production Economics*, *173*, 142-152.

Jasti, N. V. K., & Kodali, R. (2015). Lean production: literature review and trends. *International journal of production research*, *53*(3), 867-885.

Jenab, K., Wu, C., & Moslehpour, S. (2018). Design for six sigma: A review. *Management Science Letters*, *8*(1), 1-18.

Jensen, P., Hamon, E., & Olofsson, T. (2009). Product development through lean design and modularization principles. In *Annual Conference of the International Group for Lean Construction: 13/07/2009-19/07/2009* (pp. 465-474).

Junior, M. L., & Godinho Filho, M. (2010). Variations of the kanban system: Literature review and classification. *International journal of production economics*, *125*(1), 13-21.

Jurík, L., Horňáková, N., & Domčeková, V. (2020). The application of smed method in the industrial enterprise. *Acta logistica*, *7*(4), 269-281.

Kaasinen, E., Anttila, A. H., Heikkilä, P., Laarni, J., Koskinen, H., & Väätänen, A. (2022). Smooth and resilient human–machine teamwork as an industry 5.0 design challenge. *Sustainability*, *14*(5), 2773.

Kabadurmus, O., & Durmusoglu, M. B. (2020). Design of pull production control systems using axiomatic design principles. *Journal of Manufacturing Technology Management*, *31*(3), 620-647.

Kabzhassarova, M., Kulzhanova, A., Dikhanbayeva, D., Guney, M., & Turkyilmaz, A. (2021). Effect of Lean4. 0 on sustainability performance: a review. *Procedia CIRP*, *103*, 73-78.

Kasarda, M. E., Terpenny, J. P., Inman, D., Precoda, K. R., Jelesko, J., Sahin, A., & Park, J. (2007). Design for adaptability (DFAD)—a new concept for achieving sustainable design. *Robotics and Computer-Integrated Manufacturing*, *23*(6), 727-734.

Khakpour, R., Ebrahimi, A., & Seyed-Hosseini, S. M. (2024). SMED 4.0: a development of single minute exchange of die in the era of Industry 4.0 technologies to improve sustainability. *Journal of Manufacturing Technology Management*, *35*(3), 568-589.

Kjellsen, H. S., Ramillon, Q. J., Dreyer, H. C., & Powell, D. J. (2021). Heijunka 4.0–key enabling technologies for production levelling in the process industry. In *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems: IFIP WG 5.7 International Conference, APMS 2021, Nantes, France, September 5–9, 2021, Proceedings, Part I* (pp. 704-711). Springer International Publishing.

Klein, M., & Gutowska, E. (2022). The role of restorative design in the achieving principles of Industry 5.0.

Klemke, T., & Nyhuis, P. (2009). Lean changeability–evaluation and design of lean and transformable factories. *International Journal of Economics and Management Engineering 3 (2009)*, 454-461.

Kleszcz, D. (2018). Barriers and opportunities in implementation of Lean Manufacturing tools in the ceramic industry. *Production Engineering Archives*, *19*.

Ko, Y. T., Chen, M. S., Yang, C. C., & Zheng, M. C. (2015). Modelling a contradiction-oriented design approach for innovative product design. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *229*(1_suppl), 199-211.

Kolanjiappan, S. (2015). Innovative approach in introducing lean manufacturing tools in maintenance of aircraft. *Applied Mechanics and Materials*, *766*, 1190-1195.

Kolberg, D., & Zühlke, D. (2015). Lean automation enabled by industry 4.0 technologies. *IFAC-PapersOnLine*, *48*(3), 1870-1875.

Korchagin, A., Deniskin, Y., Pocebneva, I., & Vasilyeva, O. (2022). Lean Maintenance 4.0: implementation for aviation industry. *Transportation Research Procedia*, *63*, 1521-1533.

Kose, Y., Muftuoglu, S., Cevikcan, E., & Durmusoglu, M. B. (2022). Axiomatic design for lean autonomous maintenance system: an application from textile industry. *International Journal of Lean Six Sigma*, *14*(3), 555-587.

Kovari, A. (2025). A Framework for Integrating Vision Transformers with Digital Twins in Industry 5.0 Context. *Machines*, *13*(1), 36.

Kowalski, A., Waszkowski, R., & Ratushnyi, V. (2020, September). The use of Lean Manufacturing principles to improve production processes by better designing of assembly cells. In *IOP Conference Series: Materials Science and Engineering* (Vol. 916, No. 1, p. 012053). IOP Publishing.

Kumar, N., & Mathiyazhagan, K. (2020). Sustainability in lean manufacturing: a systematic literature review. *International Journal of Business Excellence*, *20*(3), 295-321.

Kumaresan, K. S., & Saman, M. Z. M. (2011). Integration of SMED and Triz in improving productivity at semiconductor industry. *Jurnal Mekanikal*.

Kuo, T. C., Huang, S. H., & Zhang, H. C. (2001). Design for manufacture and design for 'X': concepts, applications, and perspectives. *Computers & industrial engineering*, *41*(3), 241-260.

Kusiak, A. (2020). Open manufacturing: a design-for-resilience approach. *International Journal of Production Research*, *58*(15), 4647-4658.

Laudante, E. (2017). Industry 4.0, Innovation and Design. A new approach for ergonomic analysis in manufacturing system. *The Design Journal*, *20*(sup1), S2724-S2734.

Leng, J., Guo, J., Xie, J., Zhou, X., Liu, A., Gu, X., ... & Wang, L. (2024). Review of manufacturing system design in the interplay of Industry 4.0 and Industry 5.0 (Part I): Design thinking and modeling methods. *Journal of Manufacturing Systems*, *76*, 158-187.

Leng, J., Sha, W., Wang, B., Zheng, P., Zhuang, C., Liu, Q., ... & Wang, L. (2022). Industry 5.0: Prospect and retrospect. *Journal of Manufacturing Systems*, *65*, 279-295.

León, H. C. M., & Calvo-Amodio, J. (2017). Towards lean for sustainability: Understanding the interrelationships between lean and sustainability from a systems thinking perspective. Journal of cleaner production, 142, 4384-4402.

León, H. C. M., & Farris, J. A. (2011). Lean product development research: Current state and future directions. *Engineering Management Journal*, *23*(1), 29-51.

Liverani, A., Caligiana, G., Frizziero, L., Francia, D., Donnici, G., & Dhaimini, K. (2019). Design for Six Sigma (DFSS) for additive manufacturing applied to an innovative multifunctional fan. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *13*, 309-330.

Maddikunta, P. K. R., Pham, Q. V., Prabadevi, B., Deepa, N., Dev, K., Gadekallu, T. R., ... & Liyanage, M. (2022). Industry 5.0: A survey on enabling technologies and potential applications. *Journal of industrial information integration*, *26*, 100257.

Malik, A. A., & Bilberg, A. (2019). Human centered Lean automation in assembly. *Procedia CIRP*, *81*, 659-664.

Maneschi, K., & Melhado, S. (2010). Scope of design for production of partition walls and facade coverings. *Architectural Engineering and Design Management*, *6*(1), 3-17.

Maqbool, Y., Rafique, M. Z., Hussain, A., Ali, H., Javed, S., Amjad, M. S., ... & Atif, M. (2019). An implementation framework to attain 6R-based sustainable lean implementation—a case study. *Ieee Access*, *7*, 117561-117579.

Matzka, J., Di Mascolo, M., & Furmans, K. (2012). Buffer sizing of a Heijunka Kanban system. *Journal of intelligent manufacturing*, *23*, 49-60.

Mayr, A., Weigelt, M., Kühl, A., Grimm, S., Erll, A., Potzel, M., & Franke, J. J. P. C. (2018). Lean 4.0-A conceptual conjunction of lean management and Industry 4.0. *Procedia Cirp*, *72*, 622-628.

Mettas, A. (2010). Design for reliability: Overview of the process and applicable techniques. *International Journal of Performability Engineering*, *6*(6), 577.

Metternich, J., Müller, M., Meudt, T., & Schaede, C. (2017). Lean 4.0–zwischen Widerspruch und Vision. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, *112*(5), 346-348.

Miqueo, A., Torralba, M., & Yagüe-Fabra, J. A. (2020). Lean manual assembly 4.0: A systematic review. *Applied Sciences*, *10*(23), 8555.

Mladineo, M., Ćubić, M., Gjeldum, N., & Crnjac Žižić, M. (2021). Human-centric approach of the Lean management as an enabler of Industry 5.0 in SMEs. In *10th International Conference Mechanical Technologies and Structural Materials (MTSM 2021)* (pp. 111-117).

Moraes, A., Carvalho, A. M., & Sampaio, P. (2023). Lean and Industry 4.0: a review of the relationship, its limitations, and the path ahead with Industry 5.0. *Machines*, *11*(4), 443.

Mörtl, M., & Schmied, C. (2015). Design for cost—a review of methods, tools and research directions. *Journal of the Indian Institute of Science*, *95*(4), 379-404.

Mørup, M. (1992). A new design for quality paradigm. *Journal of Engineering Design*, *3*(1), 63-80.

Mostafa, S., Dumrak, J., & Soltan, H. (2015). Lean maintenance roadmap. *Procedia Manufacturing*, *2*, 434-444.

Mourtzis, D., Angelopoulos, J., Papadokostakis, M., & Panopoulos, N. (2022). Design for 3D Printing of a Robotic Arm Tool Changer under the framework of Industry 5.0. *Procedia CIRP*, *115*, 178-183.

Mrabti, A., Bouajaja, S., Hachicha, H. K., & Nouri, K. (2023). Digital 5S: a case study of an Automotive wiring industry. In *ITM Web of Conferences* (Vol. 52, p. 01005). EDP Sciences.

Mrugalska, B., & Wyrwicka, M. K. (2017). Towards lean production in industry 4.0. *Procedia engineering*, *182*, 466-473.

Naciri, L., Mouhib, Z., Gallab, M., Nali, M., Abbou, R., & Kebe, A. (2022). Lean and industry 4.0: A leading harmony. *Procedia Computer Science*, *200*, 394-406.

Navas, H. V., & Machado, V. A. C. (2015). "The Lifeline" of Technical Systems in a TRIZ-LEAN Environment. *Procedia Engineering*, *131*, 232-236.

Navas, H. V., & Machado, V. C. (2013). Systematic innovation for lean supply chain management. In *22nd International Conference on Production Research, Brazil. DOI* (Vol. 10).

Navtn-Chandra, D. (1994). The recovery problem in product design. *Journal of Engeering Design*, *5*(1), 65-86.

Newcomb, P. J., Bras, B., & Rosen, D. W. (1996, August). Implications of modularity on product design for the life cycle. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 97607, p. V004T04A006). American Society of Mechanical Engineers.

Ng, R., Low, J. S. C., & Song, B. (2015). Integrating and implementing Lean and Green practices based on proposition of Carbon-Value Efficiency metric. *Journal of Cleaner Production*, *95*, 242-255.

Nunes, M. L., Pereira, A. C., & Alves, A. C. (2017). Smart products development approaches for Industry 4.0. *Procedia manufacturing*, *13*, 1215-1222.

Ohno, T. (1988). Toyota production system: beyond large-scale production. Diamond. Inc., Tokyo.

Ohno, Taiichi. 1982. "How the Toyota Production System Was Created." Japanese Economic Studies 10(4): 83–101.

Omogbai, O., & Salonitis, K. (2017). The implementation of 5S lean tool using system dynamics approach. *Procedia cirp*, *60*, 380-385.

Orso, V., Ziviani, R., Bacchiega, G., Bondani, G., Spagnolli, A., & Gamberini, L. (2022). Employee-centric innovation: Integrating participatory design and video-analysis to foster the transition to Industry 5.0. *Computers & Industrial Engineering*, *173*, 108661.

Peeters, J. R. (2012). Design for end of life: a design methodology for the early stages of an innovation process. In *DS 74: Proceedings of the 14th International Conference on Engineering & Product Design Education (E&PDE12) Design Education for Future Wellbeing, Antwerp, Belguim, 06-07.9. 2012* (pp. 185-190).

Perico, P., & Mattioli, J. (2020, September). Empowering process and control in lean 4.0 with artificial intelligence. In *2020 third international conference on artificial intelligence for industries (ai4i)* (pp. 6-9). IEEE.

Peruzzini, M., Prati, E., & Pellicciari, M. (2024). A framework to design smart manufacturing systems for Industry 5.0 based on the human-automation symbiosis. *International journal of computer integrated manufacturing*, *37*(10-11), 1426-1443.

Possamai, O., & Ceryno, P. S. (2008). Lean approach applied to product development. *Product: Management and Development*, *6*(2), 157-165.

Potthoff, L., & Gunnemann, L. (2023). Resilience of lean production systems: a systematic literature review. *Procedia CIRP*, *120*, 1315-1320.

Powell, D. J. (2024). Artificial intelligence in lean manufacturing: digitalization with a human touch?. *International Journal of Lean Six Sigma*, *15*(3), 719-729.

Qureshi, K. M., Mewada, B. G., Kaur, S., & Qureshi, M. R. N. M. (2023). Assessing lean 4.0 for industry 4.0 readiness using PLS-SEM towards sustainable manufacturing supply chain. *Sustainability*, *15*(5), 3950.

Rahardjo, B., & Wang, F. K. (2022). Lean Six Sigma tools in Industry 5.0: a sustainable innovation framework. *Available at SSRN 4160391*.

Rahardjo, B., Wang, F. K., Lo, S. C., & Chu, T. H. (2024). A sustainable innovation framework based on lean six sigma and industry 5.0. *Arabian Journal for Science and Engineering*, *49*(5), 7625-7642.

Rahardjo, B., Wang, F. K., Yeh, R. H., & Chen, Y. P. (2023). Lean manufacturing in industry 4.0: a smart and sustainable manufacturing system. *Machines*, *11*(1), 72.

Rauch, E., & Brown, C. A. (2021). Teaching axiomatic design for a long-term sustainable introduction of industry 4.0 in SMEs. *Procedia CIRP*, *96*, 169-174.

Rauch, E., Dallasega, P., & Matt, D. T. (2016). The way from lean product development (LPD) to smart product development (SPD). *Procedia CIRP*, *50*, 26-31.

Reinman, G., Ayer, T., Davan, T., Devore, M., Finley, S., Glanovsky, J., ... & Yudichak, D. (2012). Design for variation. *Quality Engineering*, *24*(2), 317-345.

Reke, E., Powell, D., & Mogos, M. F. (2022). Applying the fundamentals of TPS to realize a resilient and responsive manufacturing system. *Procedia CIRP*, *107*, 1221-1225.

Romeira, B., Moura, A., & Robaina, M. (2020, August). The kanban system's environmental impacts: A comparative study. In *Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management, Detroit, Michigan, USA* (pp. 1396-1407).

Rose, C. M. (2001). *Design for environment: a method for formulating product end-of-life strategies*. Stanford University.

Rossi, A. H. G., Marcondes, G. B., Pontes, J., Leitao, P., Treinta, F. T., De Resende, L. M. M., ... & Yoshino, R. T. (2022). Lean tools in the context of industry 4.0: literature review, implementation and trends. *Sustainability*, *14*(19), 12295.

Ruano, M., & Huang, C. Y. (2023). A novel approach to service design within the tourism industry: creating a travel package with AHP-TRIZ integration. *Systems*, *11*(4), 178.

Sá, J. C., Manuel, V., Silva, F. J. G., Santos, G., Ferreira, L. P., Pereira, T., & Carvalho, M. (2021, October). Lean Safety-assessment of the impact of 5S and Visual Management on safety. In *IOP conference series: Materials science and engineering* (Vol. 1193, No. 1, p. 012049). IOP Publishing.

Sadeghi, L., Dantan, J. Y., Siadat, A., & Marsot, J. (2016). Design for human safety in manufacturing systems: applications of design theories, methodologies, tools and techniques. *Journal of engineering design*, *27*(12), 844-877.

Sadeghi, L., Mathieu, L., Tricot, N., & Al Bassit, L. (2015). Developing a safety indicator to measure the safety level during design for safety. *Safety science*, *80*, 252-263.

Sadeghi, L., Mathieu, L., Tricot, N., Al Bassit, L., & Ghemraoui, R. (2013a). Toward design for safety Part 1: Functional reverse engineering driven by axiomatic design. In *International Conference on Axiomatic Design, 7th ICAD* (pp. 27-28).

Sadeghi, L., Mathieu, L., Tricot, N., Al Bassit, L., & Ghemraoui, R. (2013b, June). Toward design for safety part 2: functional re-engineering using axiomatic design and FMEA. In *proceedings of the 7th international conference on axiomatic design, ICAD*.

Sassanelli, C., Pezzotta, G., Pirola, F., Terzi, S., & Rossi, M. (2016). Design for Product Service Supportability (DfPSS) approach: a state of the art to foster Product Service System (PSS) design. *Procedia CIRP*, *47*, 192-197.

Schumacher, S., Hall, R., Bildstein, A., & Bauernhansl, T. (2022). Toolbox lean 4.0-development and implementation of a database approach for the management of digital methods and tools. *Procedia CIRP*, *107*, 776-781.

Schumacher, S., Hall, R., Bildstein, A., & Bauernhansl, T. (2023). Lean Production Systems 4.0: systematic literature review and field study on the digital transformation of lean methods and tools. *International Journal of Production Research*, *61*(24), 8751-8773.

Sheldon, D. F., Huang, G. Q., & Perks, R. (1991). Design for cost: past experience and recent development. *Journal of Engineering Design*, *2*(2), 127-139.

Shirwaiker, R. A., & Okudan, G. E. (2008). Triz and axiomatic design: a review of case-studies and a proposed synergistic use. *Journal of Intelligent Manufacturing*, *19*, 33-47.

Silva, S., Sá, J. C., Silva, F. J., Ferreira, L. P., & Santos, G. (2019, November). Lean Green—The importance of integrating environment into lean philosophy—A case study. In *European Lean Educator Conference* (pp. 211-219). Cham: Springer International Publishing.

Singh, R., Gohil, A. M., Shah, D. B., & Desai, S. (2013). Total productive maintenance (TPM) implementation in a machine shop: A case study. *Procedia Engineering*, *51*, 592-599.

Sithole, C., Gibson, I., & Hoekstra, S. (2021). Evaluation of the applicability of design for six sigma to metal additive manufacturing technology. *Procedia Cirp*, *100*, 798-803.

Slim, R., Houssin, R., Coulibaly, A., & Chibane, H. (2021a). Lean System Design Framework Based on Lean Functionalities and Criteria Integration in Production Machines Design Phase. *FME Transactions*, *49*(3).

Slim, R., Houssin, R., Coulibaly, A., Hanifi, M., & Chibane, H. (2021b). Framework for Resolving Problems Resulting from Lean Integration from the Early Design Phases of Production 3D Printing Machine. *FME Transactions*, *49*(2).

Slim, R., Rémy, H., & Amadou, C. (2018). Convergence and contradiction between Lean and Industry 4.0 for inventive Design of smart production systems. In *Automated Invention for Smart Industries: 18th International TRIZ Future Conference, TFC 2018, Strasbourg, France, October 29–31, 2018, Proceedings* (pp. 141-153). Springer International Publishing.

Smets, L. P., van Houtum, G. J., & Langerak, F. (2012). Design for availability: A holistic approach to create value for manufacturers and customers of capital goods. *Journal of Systems Science and Systems Engineering*, *21*, 403-421.

Souchkov, V., & Mars, N. (1998). Knowledge-based support for innovative design. *Univ. Twente, Netherlands, No. C*.

Stadnicka, D., & Antonelli, D. (2019). Human-robot collaborative work cell implementation through lean thinking. *International Journal of Computer Integrated Manufacturing*, *32*(6), 580-595.

Suarez-Fernandez de Miranda, S., Aguayo-González, F., Salguero-Gómez, J., & Ávila-Gutiérrez, M. J. (2020). Life cycle engineering 4.0: A proposal to conceive manufacturing systems for industry 4.0 centred on the human factor (DfHFinI4. 0). *Applied Sciences*, *10*(13), 4442.

Suh, N. P. (1990). The Principles of Design, New York: Oxford Univ.

Suh, Nam P, and Nam Pyo Suh. 2001. 4 Axiomatic Design: Advances and Applications. Oxford university press New York.

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., ... & Nee, A. Y. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, *57*(12), 3935-3953.

Thomaz, J. P. F., & Bispo, H. I. (2022). Lean manufacturing and industry 4.0/5.0: applied research in the Portuguese cork industry. In *Increasing Supply Chain Performance in Digital Society* (pp. 101-130). IGI Global.

Tortorella, M. (2015). *Reliability, maintainability, and supportability: best practices for systems engineers*. John Wiley & Sons.

Tosi, F., & Tosi, F. (2020). *Design for ergonomics* (pp. 31-45). Springer International Publishing.

Turner, C., & Oyekan, J. (2023). Manufacturing in the age of human-centric and sustainable industry 5.0: application to holonic, flexible, reconfigurable and smart manufacturing systems. *Sustainability*, *15*(13), 10169.

Uhlmann, E., Hohwieler, E., & Geisert, C. (2017). Intelligent production systems in the era of Industrie 4.0–changing mindsets and business models. *Journal of Machine Engineering*, *17*(2), 5-24.

Valamede, L. S., & Akkari, A. C. S. (2020). Lean 4.0: A new holistic approach for the integration of lean manufacturing tools and digital technologies. *International Journal of Mathematical, Engineering and Management Sciences*, *5*(5), 851.

Valamede, L. S., & Akkari, A. C. S. (2021, October). Lean 4.0: digital technologies as strategies to reduce waste of lean manufacturing. In *Brazilian Technology Symposium* (pp. 74-83). Cham: Springer International Publishing.

Valentinčič, J., Brissaud, D., & Junkar, M. (2007). A novel approach to DFM in toolmaking: a case study. *International Journal of Computer Integrated Manufacturing*, *20*(1), 28-38.

Vaneker, T., & Van Diepen, T. (2016). Design support for maintenance tasks using TRIZ. *Procedia CIRP*, *39*, 67-72.

Vasanthakumar, C., Vinodh, S., & Ramesh, K. (2016). Application of interpretive structural modelling for analysis of factors influencing lean remanufacturing practices. *International Journal of Production Research*, *54*(24), 7439-7452.

Verrier, B., Rose, B., & Caillaud, E. (2016). Lean and Green strategy: the Lean and Green House and maturity deployment model. *Journal of cleaner production*, *116*, 150-156.

Vinodh, S., & Aravindraj, S. (2012). Axiomatic modeling of lean manufacturing system. *Journal of Engineering, Design and Technology*, *10*(2), 199-216.

Wagner, T., Herrmann, C., & Thiede, S. (2017). Industry 4.0 impacts on lean production systems. *Procedia Cirp*, *63*, 125-131.

Wan, P. K., & Leirmo, T. L. (2023). Human-centric zero-defect manufacturing: State-of-the-art review, perspectives, and challenges. *Computers in Industry*, *144*, 103792.

Wang, F. K., Rahardjo, B., & Rovira, P. R. (2022). Lean six sigma with value stream mapping in industry 4.0 for human-centered workstation design. *Sustainability*, *14*(17), 11020.

Wang, Y., Yu, T., & Wang, K. (Eds.). (2024). *Advanced Manufacturing and Automation XIII*. Springer.

Wolniak, R. (2024). The usage of Poka-Yoka in Industry 4.0 conditions. *Zeszyty Naukowe. Organizacja i Zarządzanie/Politechnika Śląska*.

Womack, J. P., & Jones, D. T. (1997). Lean thinking—banish waste and create wealth in your corporation. *Journal of the operational research society*, *48*(11), 1148-1148.

Womack, J. P., Jones, D. T., & Roos, D. (1991). The Machine That Changed the World: The Story of Lean Production. HarperCollins. *Estados Unidos de América*.

Xiaochuan, C., Jianguo, Y., Beizhi, L., & Xin-An, F. (2004, June). Methodology and technology of design for cost (DFC). In *Fifth World Congress on Intelligent Control and Automation (IEEE Cat. No. 04EX788)* (Vol. 3, pp. 2834-2840). IEEE.

Yang, S., MR, A. R., Kaminski, J., & Pepin, H. (2018). Opportunities for industry 4.0 to support remanufacturing. *Applied Sciences*, *8*(7), 1177.

Zizic, M. C., Mladineo, M., Gjeldum, N., & Celent, L. (2022). From industry 4.0 towards industry 5.0: A review and analysis of paradigm shift for the people, organization and technology. *Energies*, *15*(14), 5221.

Résumé en Français

Contribution à l'Intégration du Lean dans la Conception Inventive des Systèmes Manufacturiers dans le Contexte de l'Industrie 5.0

1. Introduction et Contexte

Ma thèse s'inscrit dans le cadre d'une collaboration scientifique entre l'équipe CSIP du laboratoire ICUBE de l'Université de Strasbourg et le laboratoire OLID de l'Institut Supérieur de Gestion Industrielle de Sfax. L'équipe CSIP se consacre à la formalisation de l'activité d'invention à travers l'application de méthodes basées sur le TRIZ dans la conception de produits/systèmes, en intégrant les perspectives des sciences de l'ingénieur et de l'information. Le laboratoire OLID se concentre sur l'optimisation, la prise de décision, la logistique et l'informatique décisionnelle.

L'approche actuelle de l'industrie pour améliorer la performance des systèmes en appliquant les outils Lean lors des phases opérationnelles est curative. Bien que cette approche offre de nombreux avantages, elle présente également plusieurs limitations majeures, qui constituent le cœur de cette thèse. Ces limitations incluent les contraintes inhérentes à la conception des systèmes manufacturiers existants, qui peuvent ne pas s'adapter aux changements liés au Lean, telles que les limitations des équipements, la complexité des processus actuels et la résistance au changement des employés habitués aux procédures traditionnelles. De plus, des investissements importants en termes de temps et de coût sont souvent nécessaires pour mettre en œuvre les outils Lean ou intégrer de nouvelles technologies afin de surmonter différentes contraintes et gaspillages, qui pourraient être évités plus simplement en prenant en compte les exigences Lean dès le départ. Ces ajustements peuvent avoir un impact sur le comportement des opérateurs et leurs interactions avec les machines, entraînant une diminution de la coopération et une résistance au nouveau système.

Les entreprises ne reconnaissent souvent l'importance de la mise en œuvre des outils Lean qu'une fois que les défauts et les gaspillages apparaissent dans le processus de fabrication. Cependant, nous proposons de changer de perspective et de passer d'une approche réactive ou curative à une approche proactive et préventive. Cela signifie redéfinir la manière dont le Lean est conçu: au lieu d'attendre l'apparition de problèmes de performance pour appliquer Lean comme solution, celui-ci devrait être adopté de manière préventive dès la phase de conception. En essence, cette transition vers une vision préventive de l'intégration du Lean implique d'incorporer les exigences des outils Lean dès les premières phases de conception des systèmes manufacturiers.

Après la tendance Lean, les entreprises s'appuient de plus en plus sur les technologies récentes pour améliorer leurs performances en intégrant des solutions de l'Industrie 4.0 (I4.0). Pour combiner Lean et I4.0, la littérature utilise des termes tels que Lean 4.0, automatisation Lean, fabrication Lean intelligente et Lean I4.0. Cependant, l'adoption des technologies I4.0 a conduit à l'évolution des systèmes de fabrication traditionnels vers des systèmes numérisés.

Lorsque les entreprises ont commencé à adopter l'I4.0 et à se concentrer sur la relation potentielle entre Lean et I4.0, la Cinquième Révolution Industrielle est apparue. En tirant parti de l'efficacité et de la performance des processus de fabrication, l'I4.0 se concentre principalement sur le changement de paradigme induit par les nouvelles technologies, mais les aspects humains et environnementaux ont reçu moins d'attention. Selon la Commission européenne en 2021, l'Industrie 5.0 (I5.0) complète le paradigme I4.0 existant pour concevoir les systèmes du futur, afin de mieux répondre aux objectifs industriels et technologiques sans compromettre la performance socio-économique et environnementale. L'I5.0 comprend trois principes fondamentaux: Centrée sur l'humain, la durabilité et la résilience.

Lean peut contribuer à divers critères de performance, que ce soit de manière indépendante ou en synergie avec d'autres concepts dans le cadre de l'I4.0 et de l'I5.0, tels que l'automatisation, la flexibilité et la durabilité. Son intégration dès la phase de conception est large, englobant les composants du système, la conception des flux et le comportement global du système. Cependant, garantir que les systèmes de fabrication soient intrinsèquement basés sur les principes Lean dès le départ demeure un défi. Cette thèse vise à développer une approche de conception holistique qui permet aux concepteurs d'intégrer les caractéristiques de performance souhaitées dès les premières phases de conception en intégrant systématiquement les exigences Lean dans le contexte de l'I5.0. La Figure 1 illustre la vision globale de la thèse.

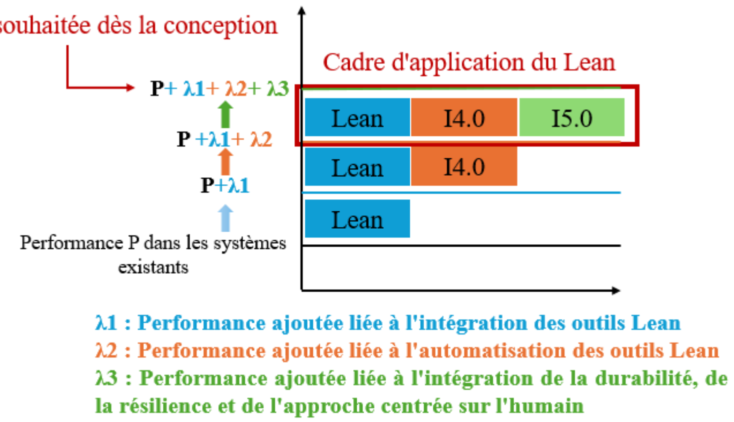

Figure 1 : Vision Globale de la Thèse

En examinant les synergies entre les principes du Lean, de l'I4.0 et de l'I5.0, cette thèse démontre comment le Lean s'est intrinsèquement aligné avec les principes fondamentaux de l'I5.0 bien avant son émergence officielle. En intégrant les avancées technologiques de l'I5.0 avec les concepts classiques du Lean qui soutiennent ses valeurs fondamentales, notre objectif est de développer le paradigme Lean 5.0, intégrant les avancées numériques avec des pratiques de fabrication centrées sur l'humain, durables et résilientes.

Dans notre recherche, nous visons à proposer le concept de “Design for Lean 5.0”, qui cherche à surmonter les limitations des méthodologies traditionnelles de “Design for X (DfX)” en combinant les divers critères de performance que ces méthodologies mettent en avant. L'approche que nous proposons intègre les exigences Lean pour satisfaire ces critères tout en les alignant avec les principes de l'I5.0. Dans ce contexte, nous préconisons une nouvelle vision qui conceptualise les exigences Lean comme l'écart entre l'état actuel indésirable (ou l'état devant être identifié dans la conception d'un nouveau système) et les opérations optimales, axées sur la performance et alignées avec les principes Lean pour la conception de systèmes futurs. Nous proposons un processus systématique visant à combler les limitations des applications Lean dans les systèmes existants et à concevoir des systèmes qui intègrent de manière inhérente les exigences nécessaires, éliminant ainsi la dépendance aux outils Lean traditionnels dans les conceptions de systèmes futurs. Cette approche permet aux entreprises d'atteindre des systèmes plus efficaces et autogérés sans dépendre d'interventions Lean extensives, tout en intégrant les principes et technologies de l'I5.0.

Nous examinons les limitations des systèmes actuels et proposons des stratégies pour les atténuer lors de la phase de conception des systèmes de fabrication. Notre approche préconise un passage d'une approche réactive et corrective à une approche proactive et préventive. En abordant les défis existants de manière proactive dès le début, nous visons à formuler et intégrer plusieurs exigences des outils Lean dans un contexte I5.0 pour concevoir des systèmes durables et adaptables, nécessitant une application minimale de Lean (Leanless), avec un minimum de gaspillages et en tenant compte des considérations centrées sur l'humain.

Bien que l'intégration des exigences Lean et I5.0 lors de la phase de conception soit importante, le processus de combinaison et d'intégration de multiples exigences et de leurs paramètres associés peut conduire à un système complexe, entraînant parfois des contradictions. Pour résoudre cette complexité, nous avons choisi d'utiliser la méthode de Conception Axiomatique afin de proposer des solutions indépendantes pour cette intégration, d'identifier les paramètres correspondants et de définir les mécanismes et outils pour son intégration. De plus, nous proposons une méthodologie basée sur les principes TRIZ, qui permet d'identifier et de résoudre les contradictions pouvant découler des paramètres résultants dès la phase de conception, évitant ainsi tout impact négatif sur les performances globales du système. La Figure 2 résume les méthodes utilisées dans notre méthodologie et leur utilité.

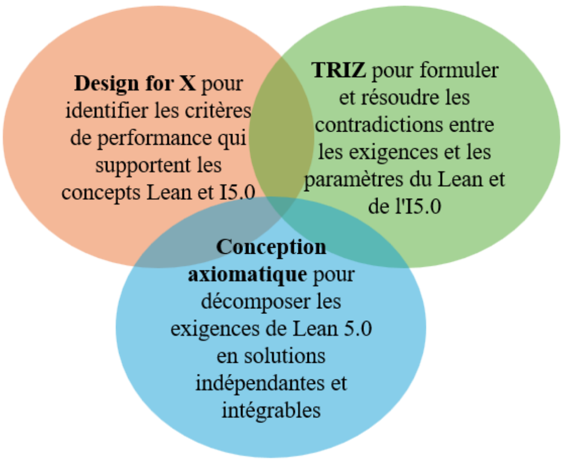

Figure 2 : Méthodes Appliquées dans Notre Méthodologie

Cette thèse vise à analyser la relation complémentaire entre Lean, I4.0 et I5.0 afin d'introduire le paradigme Lean 5.0 et proposer un modèle Axiomatique Lean 5.0 qui combine les exigences Lean avec les principes de l'I5.0. De plus, nous proposons une méthodologie permettant aux concepteurs de concevoir un système de fabrication inventif avec les performances souhaitées dès le départ, en intégrant les exigences et les paramètres Lean dans un contexte I5.0, et de formuler et résoudre les éventuelles contradictions pouvant découler de cette intégration.

Dans cette thèse, nous intégrons à la fois des approches de conception routinières et inventives. Plus précisément, nous utilisons la méthode DfX pour identifier les objectifs de conception applicables à différents systèmes de conception, servant de guide pour définir les exigences et les paramètres. De plus, l'accent est mis sur la décomposition du problème complexe de la conception d'un système Lean 5.0, en extrayant les problèmes les plus importants à résoudre, notamment à travers la combinaison des principes TRIZ et de la méthode de Conception Axiomatique (AD).

2. Structure de la Thèse et les Résultats

Cette thèse est structurée en Cinq Chapitres :

Chapitre I : Introduction et Problématique

Ce chapitre présente le contexte global de cette recherche, en mettant en avant son objectif principal : introduire le concept de Lean 5.0 et intégrer ses exigences dès la phase de conception des systèmes manufacturiers. Ces exigences sont déduites à partir des limitations d'application des outils Lean dans les systèmes existants. Nous proposons de les intégrer dès la phase de conception afin de réduire ou d'éliminer les interventions Lean dans les phases opérationnelles des systèmes conçus. De plus, aligner ces exigences avec les principes de l'I5.0. Nous présentons aussi les méthodes de conception utilisées dans la méthodologie proposée, notamment Design for X, TRIZ et la Conception Axiomatique.

Chapitre II : État de l'art sur l'intégration du Lean et de l'Industrie 5.0 dans la Conception des Systèmes Manufacturiers

Dans notre revue de la littérature, nous analysons d'abord la transition de l'I4.0 à l'I5.0 et identifions les principes de l'I5.0 qui répondent aux limitations de l'I4.0. Ensuite, nous effectuons une revue de la littérature pour examiner comment les principes de l'I5.0 peuvent être pris en compte dès la phase de conception. Nous explorons ensuite la combinaison du Lean et de l'I4.0, qui a conduit à des concepts tels que le Lean 4.0, et analysons l'intégration de ce concept dès la phase de conception, en soulignant ses limitations. Cette analyse nous guide dans l'exploration de la combinaison du Lean avec l'I5.0. Nous examinons également la synergie entre ces deux concepts à deux moments: Après l'annonce officielle de l'I5.0, en nous concentrant sur la synergie entre les deux concepts, et avant l'annonce officielle de l'I5.0, en étudiant les synergies entre les principes fondamentaux du Lean et de l'I5.0. Enfin, nous réalisons une revue de la littérature pour évaluer l'intégration des deux concepts dès la phase de conception. Nous avons également effectué une revue de la littérature concernant les méthodologies de conception facilitant l'intégration du Lean et de l'I5.0 dès la phase de conception. Nous avons d'abord mené une revue de la littérature de 34 méthodologies DfX pour identifier les critères de performance pertinents englobant à la fois les principes du Lean et de l'I5.0. Ensuite, nous avons examiné la méthode de Conception Axiomatique et étudié les travaux précédents ayant appliqué cette méthode pour modéliser les principes du Lean et de l'I5.0. Enfin, nous avons analysé la complémentarité entre le Lean et le TRIZ, explorant comment cette synergie contribue à faciliter l'intégration des outils et des fonctionnalités du Lean dans la conception des systèmes manufacturiers en abordant les contradictions potentielles.

Nous avons identifié huit lacunes dans les différents axes abordés lors de notre revue. Le Tableau 1 résume ces lacunes ainsi que nos contributions.

Tableau 1: Résumé des Lacunes de la Littérature et des Contributions Correspondantes

Lacunes dans la littérature	Contributions
Première Lacune: L'intégration du Lean dans la conception se concentre principalement sur l'amélioration du processus de conception lui-même, avec peu de recherches sur l'intégration du Lean pour améliorer le système conçu, qui est l'objet du processus de conception.	Notre travail s'intéresse à l'amélioration de la performance du système conçu, plutôt qu'au processus de conception, en intégrant les exigences Lean dans un contexte d'I5.0 pour répondre à plusieurs critères de performance.
Deuxième lacune: Une compréhension ambiguë des exigences Lean et un manque de lignes directrices pour intégrer ces exigences et paramètres Lean pendant la phase de conception.	Nous définissons les exigences Lean pour résoudre les problèmes liés aux processus de fabrication et proposons une nouvelle perspective où ces exigences comblent le fossé entre les limitations des systèmes existants et les conceptions futures optimales, axées sur la performance. Notre travail présente une liste de plus de 100 exigences Lean extraites de la littérature, ainsi que leurs paramètres correspondants, couvrant à la fois les domaines classiques et ceux de l'I5.0. Nous identifions les limitations de l'application des outils Lean dans les systèmes existants et dérivons les exigences fonctionnelles Lean à intégrer dès la phase de conception, afin de réduire la nécessité d'interventions Lean dans les conceptions futures des systèmes.
Troisième lacune: Les études visant à intégrer l'I5.0 dès la phase de conception, bien que peu nombreuses, ont tendance à aborder ses principes séparément, avec peu de recherches existantes se concentrant sur l'intégration des trois principes principaux de l'I5.0.	Dans notre travail, nous intégrons les exigences Lean avec les trois principes fondamentaux de l'I5.0, tout en identifiant également les technologies I5.0 qui soutiennent cette intégration.
Quatrième lacune: Manque d'études empiriques évaluant l'intégration des outils Lean 4.0 dès la phase de conception des systèmes de production.	Nous avons présenté des preuves empiriques, issues d'une enquête par questionnaire soutenue par des analyses factorielles exploratoires et confirmatoires, qui mettent en évidence l'impact de l'intégration des outils Lean 4.0 dès la phase de conception sur cinq dimensions critiques de la conception. Les détails complets de cette contribution sont publiés dans (Gdoura et al. 2024a).
Cinquième lacune: Manque d'analyse sur la relation entre les outils Lean et les principes fondamentaux de l'I5.0.	Nous analysons comment Lean a abordé la durabilité, la résilience et l'orientation humaine, même avant l'introduction officielle du concept I5.0. Cette analyse nous permet de comprendre comment Lean intègre de manière inhérente ces principes, indépendamment des avancées technologiques mises en avant dans l'I5.0.
Sixième lacune: Absence de lignes directrices et de méthodologies pour formuler et intégrer les valeurs ajoutées des outils Lean lors de la phase de conception des systèmes manufacturiers dans un contexte I5.0.	Nous proposons un modèle Axiomatique comprenant trois volets principaux : "Concevoir un système manufacturier Lean durable", "Concevoir un système manufacturier Lean résilient" et "Concevoir un système manufacturier Lean centré sur l'humain". Ce modèle sert de guide pour aligner les diverses exigences des outils Lean avec les principes de l'I5.0 et les intégrer dans la conception des systèmes manufacturiers,

Septième lacune: Absence d'un modèle Axiomatique pour concevoir un système qui intègre les outils Lean en alignement avec les principes I5.0.	tout en identifiant les paramètres de conception et les variables de processus à prendre en compte dans cette intégration.
Huitième lacune: Absence de méthodologies visant à identifier et résoudre les contradictions qui peuvent émerger de l'intégration de multiples exigences du Lean pendant la phase de conception.	Nous proposons une nouvelle méthodologie appelée “Matrice d'Intégration des Paramètres Lean 5.0”, qui repose sur les paramètres identifiés dans la littérature et ceux dérivés du modèle de conception Axiomatique. Cette méthodologie facilite l'intégration de multiples exigences Lean 5.0 dans divers conceptions de systèmes et permet la formulation et la résolution des contradictions entre différentes exigences.

Chapitre III : Une Nouvelle Méthodologie pour la Conception Inventive des Systèmes Manufacturiers Lean 5.0

Dans ce chapitre, nous présentons notre méthodologie globale pour le développement et l'intégration du Lean 5.0 dès la phase de conception des systèmes manufacturiers, en s'appuyant sur les méthodes de conception Axiomatique et TRIZ. La Figure 3 présente le cadre Lean 5.0 proposé.

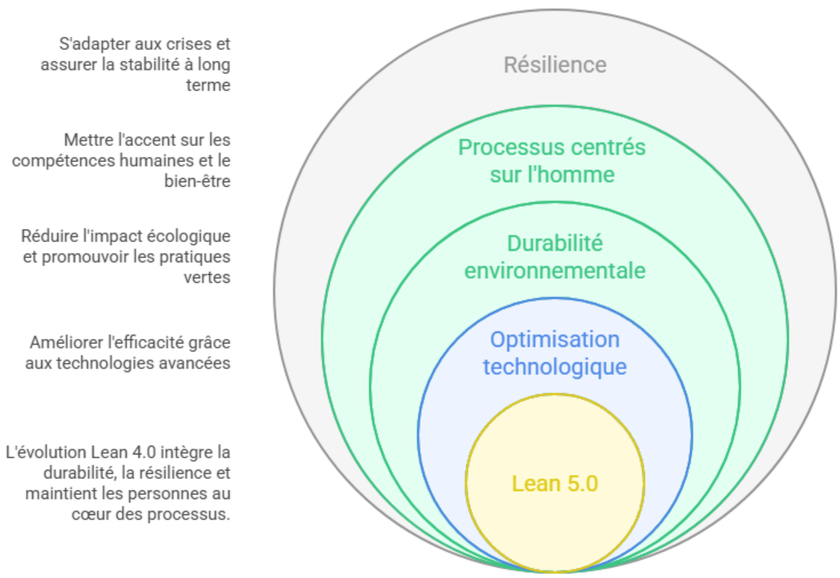

Figure 3 : Cadre du Lean 5.0

La Figure 4 présente l'ensemble du cadre de la méthodologie proposée sous la forme d'un modèle en V, qui suit une approche descendante basée sur le modèle Fonction-Comportement-Structure, garantissant un raffinement et une amélioration continus du système manufacturier à travers quatre étapes itératives: Spécification des exigences, conception conceptuelle, conception de l'incarnation et conception détaillée.

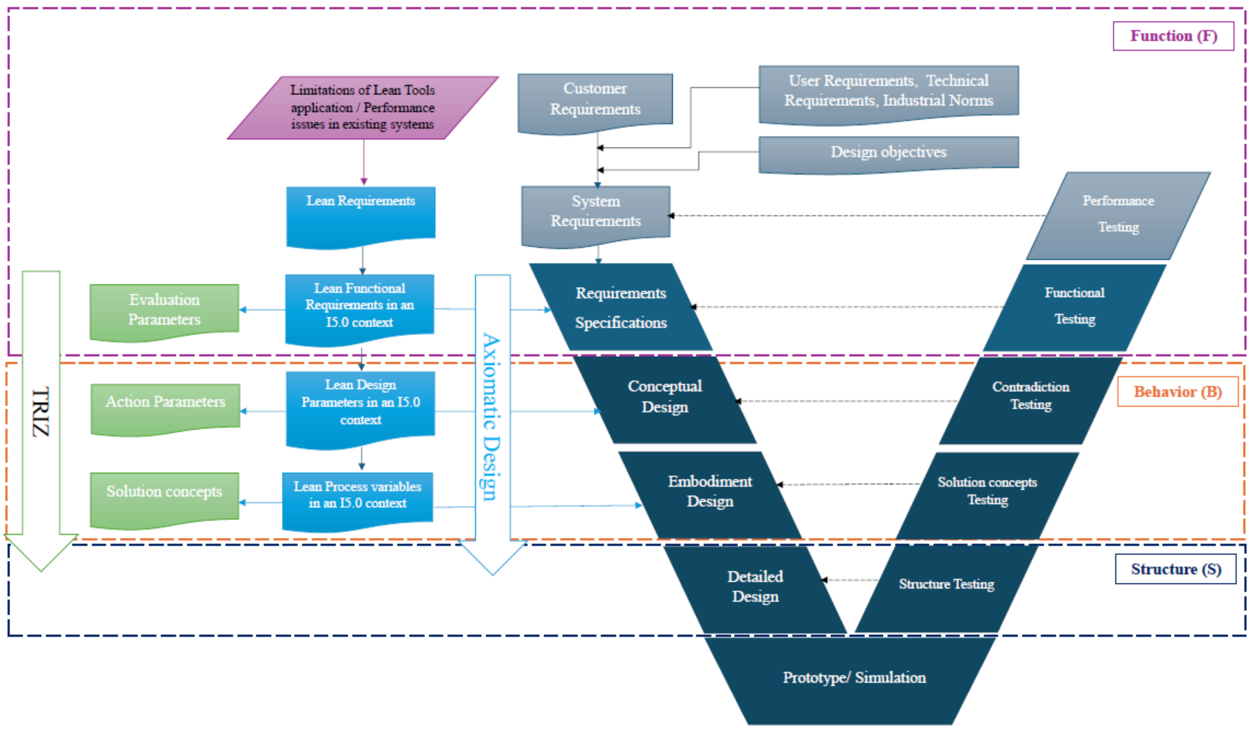

Figure 4 : Cadre de la Méthodologie Proposée "Conception pour Lean 5.0"

D'un point de vue méthodologique, notre étude propose une méthodologie composée de trois phases principales. La première phase consiste à extraire de la littérature un ensemble d'exigences Lean et leurs paramètres correspondants dans un contexte I5.0, afin de satisfaire plusieurs critères de performance identifiés à travers un examen de 34 méthodologies DfX. Dans cette phase, nous fournissons des lignes directrices comprenant une liste de plus de 100 exigences et leurs paramètres correspondants pour les chercheurs et les praticiens, illustrant comment les outils Lean peuvent être adaptés et orientés pendant la phase de conception pour satisfaire plus efficacement les principes de l'I5.0.

La deuxième phase consiste à proposer un nouveau modèle Axiomatique généralisé Lean 5.0 qui met l'accent sur l'intégration proactive des exigences Lean dans un contexte I5.0 dans la conception des systèmes manufacturiers. Ce modèle comprend trois volets principaux: "Concevoir un système manufacturier Lean durable", "Concevoir un système manufacturier Lean résilient" et "Concevoir un système manufacturier Lean centré sur l'humain". Il sert de ligne directrice pour aligner chacun des principes fondamentaux de l'I5.0 avec huit exigences fonctionnelles Lean, dérivées d'une analyse des limitations des applications des outils Lean dans les systèmes existants. De plus, le modèle proposé identifie les paramètres de conception et les variables de processus à prendre en compte dans cette intégration.

Notre recherche est originale en proposant une nouvelle feuille de route utilisant la méthode de conception Axiomatique pour la conception complète des systèmes manufacturiers Lean 5.0. La feuille de route proposée décrit la décomposition des objectifs de conception fondamentaux liés aux concepts Lean et I5.0 en objectifs de conception secondaires, permettant à l'approche AD de simplifier la conception des processus industriels. De plus, l'absence de travaux antérieurs tentant de concevoir des systèmes intégrant à la fois les principes Lean et I5.0 en utilisant la méthode AD souligne l'importance de cette étude. Elle sert de proposition fondamentale qui peut être développée davantage pour fournir des détails spécifiques à chaque domaine pour diverses industries.

Concernant notre objectif d'intégrer plusieurs exigences Lean 5.0, tenter d'incorporer leurs paramètres correspondants dérivés de notre modèle Axiomatique Lean 5.0 peut générer des contradictions. En tirant parti de la complémentarité entre les méthodes TRIZ et AD, cela nous conduit à la troisième phase majeure de notre thèse, expliquée dans le chapitre IV.

Chapitre IV: Une Nouvelle Approche basée sur TRIZ pour la Conception de Systèmes Manufacturiers Inventifs.

Cette partie consiste à proposer une nouvelle méthodologie nommée la “Matrice d'Intégration des Paramètres Lean 5.0 (L5.0PIM)”, qui vise à analyser et résoudre les contradictions découlant de l'intégration de multiples paramètres Lean 5.0 durant la phase de conception, afin de prévenir les problèmes potentiels dans le système à concevoir.

Cette matrice est composée de Paramètres d'Action Généralisés (SAPs) dérivés du modèle Axiomatique, ainsi que des Paramètres d'Évaluation Généralisés (SEPs) qui catégorisent plus de 100 paramètres correspondant aux exigences Lean extraites de la littérature.

L5.0PIM représente une première initiative pour extraire simultanément les contradictions techniques et physiques résultant de l'intégration des exigences Lean. Il formule également un système de contradictions entre divers paramètres Lean à intégrer lors de la phase de conception, tout en s'assurant que ces exigences et paramètres s'alignent constamment avec les principes de l'I5.0. L5.0PIM est composé d'un ensemble de paramètres Lean généralisés qui influencent la performance des processus de fabrication ou de production. La Figure 5 présente les étapes de la méthodologie L5.0PIM. Ces étapes sont classées en deux phases principales: Le remplissage de L5.0PIM et la résolution de problèmes.

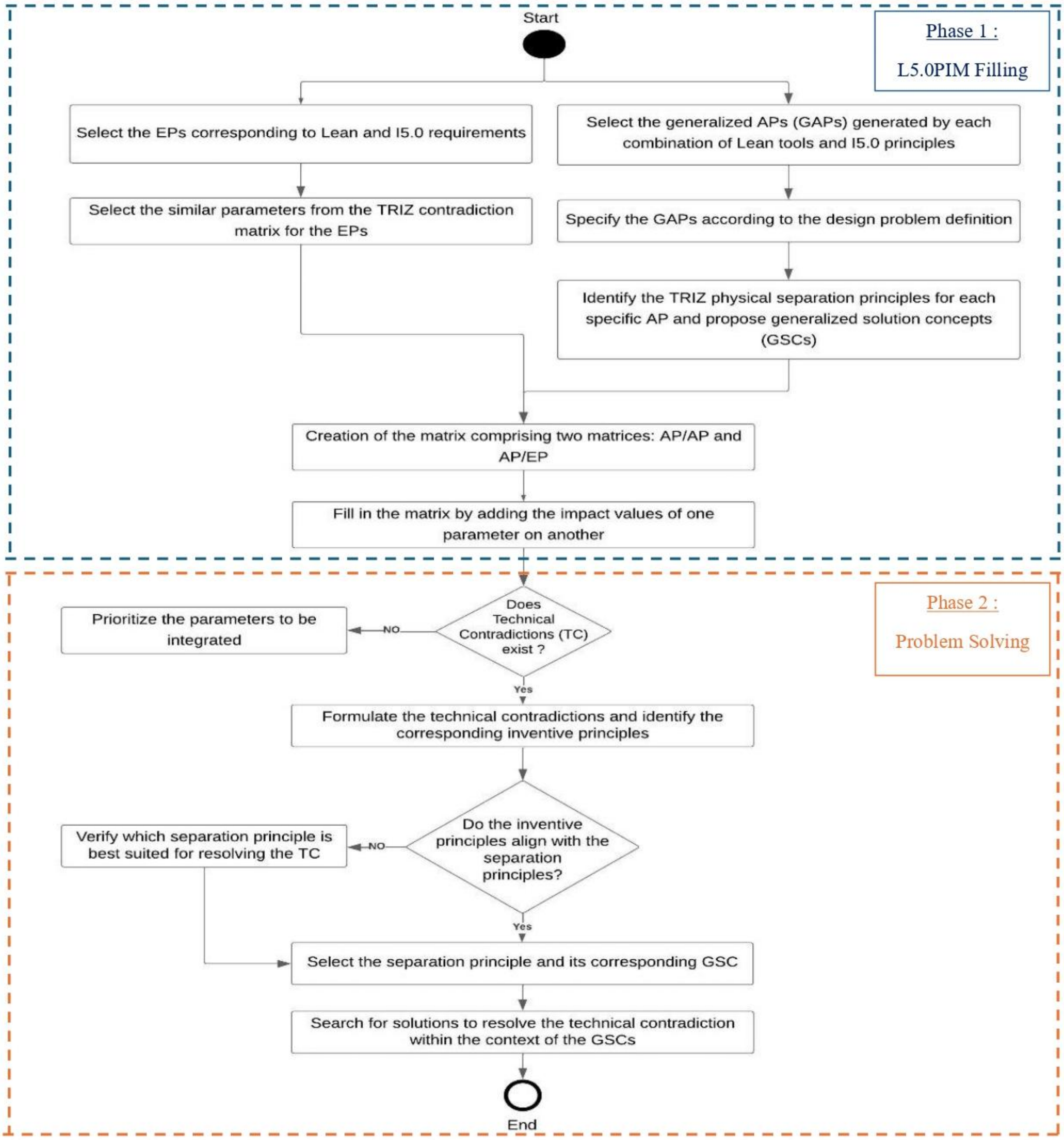

Figure 5 : Méthodologie L5.0PIM

La Figure 6 montre la structure de notre matrice, incluant certains des paramètres identifiés. Il est important de noter que la liste des paramètres dans notre matrice n'est pas exhaustive; elle représente un premier effort pour développer notre perspective actuelle, et l'approche décrite ici est considérée comme une version initiale. Cette version est destinée à servir de point de départ et peut être affinée et étendue au fil du temps, en fonction de recherches supplémentaires et des facteurs contextuels évolutifs. Nous continuons à ajouter de nouveaux paramètres au fur et à mesure que nous, ou les concepteurs, reconnaissons leurs avantages. Elle peut également servir de modèle initial pour d'autres chercheurs afin qu'ils contribuent avec des paramètres supplémentaires basés sur leurs domaines d'expertise.

							SAP \ Objective				Specific EP (SEP)			
											Min/Max	Min/Max	Min/Max	Min/Max
Lean Tool	Lean 5.0 FRs	Generalized AP (GAP)	Specific AP (SAP)	GSCs for GAPs	Separation Principles and GSCs for SAPs	Opposite values for SAP	SAP 1	SAP2	SAP3	SAPn	SEP1	SEP2	SEP3	SEPn
SMED	Sustainable Rapid Changeover	1-External Changeover	SAP 1	Quick-Change Fixtures and Mechanism	*Identified based on Problem definition*	V=Max		-1 /0/+1	-1 /0/+1	-1 /0/+1	-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
						V¯=Min					-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
	Resilient Rapid Changeover	2-Modular Equipment Design	SAP 2	Additive Manufacturing		V=Max	-1 /0/+1		-1 /0/+1	-1 /0/+1	-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
						V¯=Min					-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
	Human-Centric Rapid Changeover	3-Digital Work Instructions	SAP 3	Augmented Reality Guides		V=Max	-1 /0/+1	-1 /0/+1		-1 /0/+1	-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
						V¯=Min					-1/0/+1	-1/0/+1	-1/0/+1	-1/0/+1
5S	Sustainable Minimal Tool Use	4-Tool Removal or Standardization	SAP 4	Multi-Functional Tools		V=Max								
						V¯=Min								
	Resilient Minimal Tool Use	5-Tool Availability	SAP 5	Built-In Tool Functions		V=Max								
						V¯=Min								
	Human-Centric Minimal Tool Use	6-Identification and the localization of objects	SAP 6	Virtual tool placement guide		V¯=Min								
						V¯=Min								
TPM	Sustainable Easy Maintenance	7-Customizable Alerts	SAP 7	Visual Management and Metrics		V=Max								
						V¯=Min								
	Resilient Easy Maintenance	8-Automated Monitoring and Diagnostics	SAP 8	Predictive Maintenance Algorithms		V=Max								
						V¯=Min								
	Human-Centric Easy Maintenance	9-Operators and Maintenance Specialists Interaction	SAP 9	Reality and virtual Simulation		V=Max								
						V¯=Min								
Poka-Yoke	Sustainable Error Prevention	10-Automatic Error Detection	SAP 10	Error-Proofing Devices and Mechanisms		V=Max								
						V¯=Min								
	Resilient Error Prevention	11-Prediction Based On Past Data	SAP 11	AI Algorithms		V=Max								
						V¯=Min								
	Human-Centric Error Prevention	12-Provide Operators With Real-Time Feedback and Guidance	SAP 12	AR Guidance for Operators		V=Max								
						V¯=Min								
JIT			SAP n											
Heijunka			SAP n											
Kanban			SAP n											
VSM			SAP n											
Similar parameters of the TRIZ Contradiction Matrix											25, 33, 36…	26,39,21 …	19, 22, 23 …	…

Figure 6 : Structure du L5.0PIM

Notre approche proposée permet de résoudre simultanément les contradictions techniques et physiques, en s'assurant que les deux sont abordées dans une seule étape de conception. Elle le fait en proposant des Concepts de Solutions Généralisées (CSG) pour résoudre les contradictions physiques basées sur les principes de séparation, suivis de l'identification et de la résolution des contradictions techniques dans le contexte des CSG.

La Figure 7 explique cette approche qui permet de résoudre simultanément les contradictions techniques et physiques.

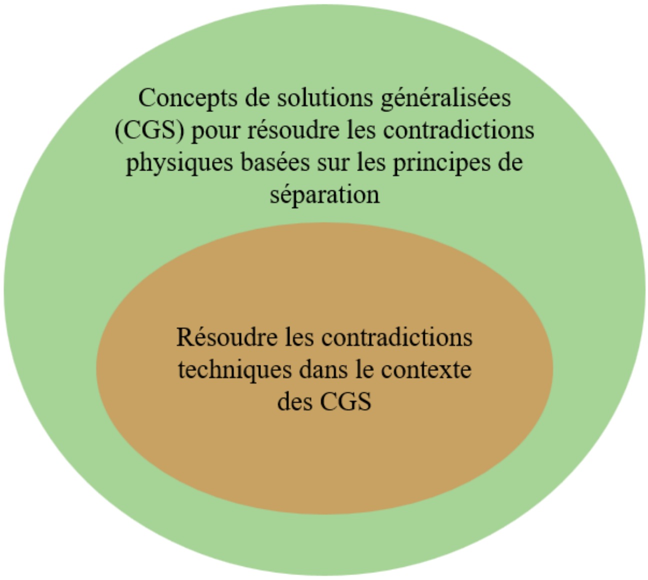

Figure 7 : Notre Approche visant à Résoudre Simultanément les Contradictions Techniques et Physiques

La méthodologie L5.0PIM est appliquée dans le système de fabrication additive dans le chapitre V.

Chapitre V : Application de L5.0PIM dans les Systèmes de Fabrication Additive : Étude de Cas

Dans ce chapitre, nous appliquons la méthode L5.0PIM au système de fabrication additive, afin d'améliorer le processus actuel tout en combinant les exigences fonctionnelles de trois outils du Lean (Juste-à-Temps, 5S et SMED) avec le principe de durabilité de l'I5.0. L5.0PIM se compose de deux matrices: La matrice SAPs/SAPs et la matrice SAPs/SEPs. Sur la base de notre analyse du AMS et des contributions d'experts, nous remplissons ces matrices en évaluant l'impact de chaque SAP sur les autres SAP et ses effets sur les SEPs. La Figure 8 montre les matrices complètes.

							SAP / Objective			Specific EP (SEP)			
										Max	Min	Min	Min
Lean Tool-Lean 5.0 FR	Lean 5.0 FR for AMS	Generalized AP (GAP)	GSC for GAP	Specific AP (SAP)	Separation Principles and GSC for SAP	Opposite values for SAP	SAP 1	SAP2	SAP3	SEP1 Part Quality	SEP2 Impression Time	SEP3 Material Usage	SEP4 Post-Processing Complexity
JIT- FR11 "Design for Sustainable Pull Production"	Minimize Print Time While Maintaining Quality	Reduce the Material Extrusion Time	External Material Application	SAP 1 Variable Fill Rate	Separation in Space "Targeted External Material Extrusion"	V=Max		-1	-1	-1	-1	-1	0
						V‾=Min				+1	+1	+1	0
5S- FR16 "Design for Sustainable Minimal Tool Use"	Avoid Non-Value-Added Operations	Avoid Excessive Support	External Support	SAP 2 Support Structures	Separation in Time "Placement of Reusable Supports"	V=Max	+1		-1	+1	+1	+1	+1
						V‾=Min				-1	-1	-1	-1
SMED-FR15 "Design for Sustainable Rapid Changeover"	Rapid Configuration	Insert External Parts	External Part Insertion Mechanism	SAP 3 Incorporate Inserts	Separation in Condition "Autonomous Integration of External Components"	V=After Printing	+1	+1		-1	-1	+1	+1
						V‾= During Printing				+1	+1	-1	-1
Similar Parameters of the TRIZ Contradiction Matrix										23	25	26	32

Figure 8 : L5.0PIM pour les Systèmes de Fabrication Additive

Sur la base de L5.0PIM, nous avons identifié trois systèmes de contradiction: Système de contradiction lié au taux de remplissage variable, Système de contradiction lié aux structures de support et Système de contradiction lié à l'incorporation d'inserts.

La Figure 9 montre ces trois systèmes de contradictions.

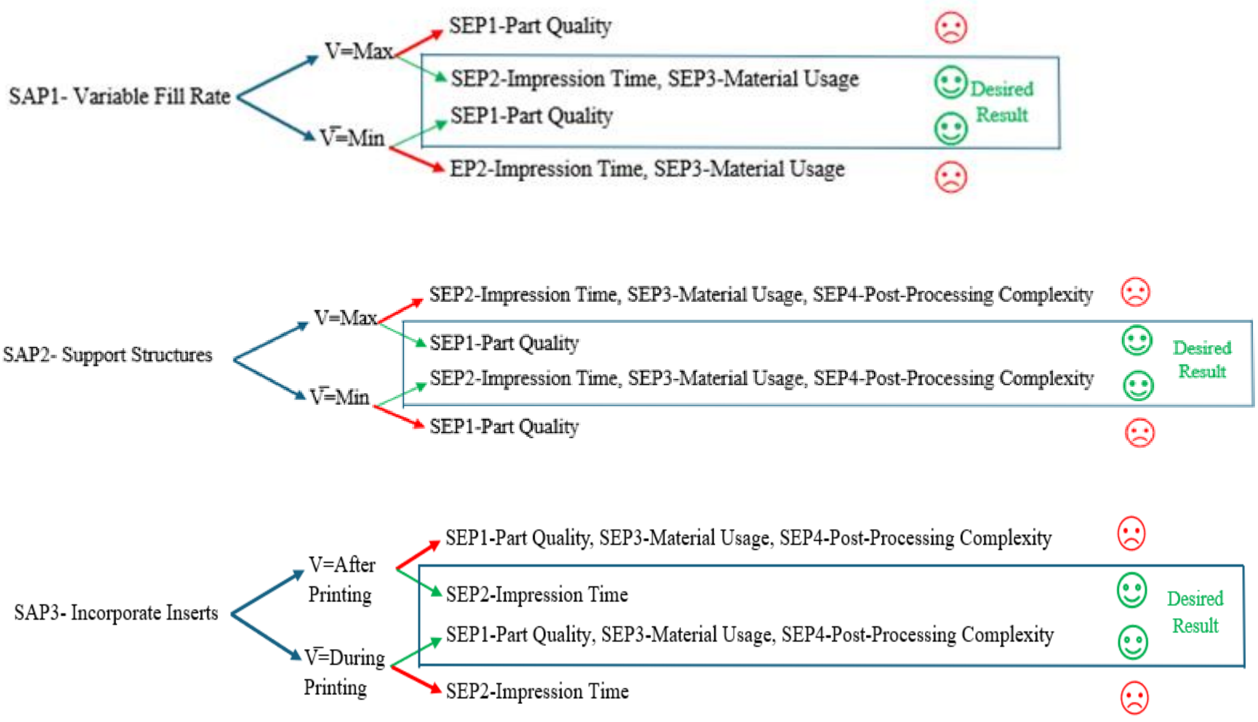

Figure 9 : Les Systèmes de Contradictions Identifiés

Le processus de résolution des contradictions commence par l'identification des paramètres correspondants à partir de la Matrice de Contradiction TRIZ (MC) pour les SEPs. Ensuite, en analysant leurs intersections dans la MC, nous déterminons les principes inventifs qui peuvent résoudre ces contradictions. Ces principes sont ensuite classés en fonction de leurs principes de séparation correspondants.

Le processus de résolution repose sur deux éléments clés: Les principes inventifs pour résoudre les Contradictions Techniques (CTs) et les Concepts de Solution Généralisée (CSG) dérivés des principes de séparation pour les Paramètres d'Action Spécifiques (SAP). Si plusieurs principes inventifs sont identifiés pour résoudre une CT, la sélection se fait en fonction du principe le mieux adapté au principe de séparation et aux GSC correspondants initialement identifiés. Si le principe sélectionné peut résoudre plusieurs CTs liées à un seul paramètre d'action, il doit être utilisé. Sinon, chaque CT doit être abordée séparément.

Sur la base de notre approche proposée, nous résolvons les contradictions identifiées et suggérons l'intégration d'un Robot Collaboratif (Cobot) avec des fonctionnalités ciblées. Le Tableau 2 résume les solutions proposées.

Tableau 2: Solutions Inventives Proposées Basées sur l'Intégration d'un Cobot

Système de Contradiction	Principe Inventive	CSG	Solutions Proposées- Fonctionnalités du Cobot
Système de contradiction lié au taux de remplissage variable	Principe 3: “Qualité locale”	Extrusion ciblée de matériau externe	Une fois les vides imprimés, le cobot, équipé d'un outil de distribution semblable à une seringue, intervient pour extruder un matériau résine dans ces vides, renforçant ainsi efficacement la structure sans compromettre le design global.
Système de contradiction lié aux structures de support	Principe 15: “Dynamique”	Placement des supports réutilisables	Le cobot insère une plaque métallique lors des moments critiques du processus d'impression, lorsque un support supplémentaire est nécessaire. Cette plaque métallique agira temporairement comme une structure de soutien, permettant la continuation fluide du processus d'impression sans avoir besoin de structures de soutien traditionnelles et intensives en matériaux.
Système de contradiction lié à l'incorporation d'inserts.	Principe 28: “Remplacer le Système Mécanique”	Intégration autonome de composants externes	Le cobot place précisément les inserts en temps réel à mesure que la pièce est construite couche par couche. Il utilise un effecteur terminal spécialisé, des pinces de précision ou des outils spécialisés pour s'assurer que les inserts sont positionnés avec précision et intégrés de manière sécurisée dans la pièce, sans perturber l'impression.

3. Limites et Perspectives

Notre étude reconnaît certaines limitations et, en même temps, présente des perspectives de recherche, notamment en ce qui concerne la méthodologie L5.0PIM. L'une des principales limitations réside dans l'inclusion de tâches manuelles, qui peuvent imposer un effort supplémentaire à la charge de travail du concepteur. Ces tâches comprennent l'identification des contradictions, la cartographie des paramètres pertinents et la détermination des solutions adaptées, un processus à la fois chronophage et susceptible d'erreurs humaines.

Pour surmonter ces défis, les futures recherches se concentreront sur l'intégration de l'Intelligence Artificielle (IA) dans la méthodologie afin d'automatiser ces tâches. En utilisant le traitement du langage naturel (NLP), le système analysera les brevets, documents techniques et études de cas pour extraire les solutions pertinentes et les associer aux contradictions identifiées. Les algorithmes d'apprentissage automatique prédiront les solutions optimales en fonction des données historiques, des meilleures pratiques et des connaissances spécifiques au domaine. Les développements futurs se concentreront sur :

1. L'identification et la spécification automatisées des paramètres généralisés, basées sur la définition du problème par le concepteur.
2. La complétion automatique de la matrice, garantissant une approche structurée et efficace de l'analyse des contradictions.
3. La génération de solutions pilotée par IA, en s'appuyant sur une base de données de brevets et d'études de cas documentées pour fournir des recommandations optimisées et basées sur des données.

Cette initiative représente une direction clé pour l'avenir de notre recherche, dans le but d'améliorer considérablement l'efficacité, l'évolutivité et l'intelligence du cadre L5.0PIM. En intégrant l'automatisation et des méthodologies pilotées par l'IA, nous visons à transformer L5.0PIM en un puissant outil de prise de décision basé sur les données, capable de gérer les contradictions complexes de conception avec plus de précision et de rapidité.

Notre vision à long terme est de développer un outil pour L5.0PIM qui offre des niveaux variables de complexité des paramètres en fonction du niveau de maturité d'une entreprise en matière de Lean et de de l'Industrie 5.0. L'outil commencera par un ensemble fondamental de paramètres moins complexes, offrant une plus grande adaptabilité pour les concepteurs. À mesure que les utilisateurs deviennent plus compétents, l'outil introduira progressivement des matrices plus complexes et des paramètres supplémentaires, améliorant ainsi ses capacités et soutenant des applications plus avancées.

Une direction potentielle pour les travaux futurs est l'intégration de l'analyse de sensibilité, ce qui pourrait offrir des informations précieuses pour valider l'indépendance des solutions dans le modèle Axiomatique Lean 5.0 et confirmer leur efficacité à travers différents contextes de fabrication. Cette approche permettrait d'optimiser et de perfectionner davantage les systèmes Lean 5.0.