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Contribution à l'amélioration de la performance des systèmes de production et de service par la prise en compte des principes de Lean dès la phase de conception dans le cadre de l'Industrie 4.0

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INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES STRASBOURG

Contribution à l'amélioration de la performance des systèmes de production et de service par la prise en compte des principes de Lean dès la phase de conception dans le cadre de l'Industrie 4.0

Résumé

Lean est une approche qui vise à optimiser la performance globale d'un système de production en développant des méthodes d'amélioration permettant d'éliminer les gaspillages dans tout le processus industriel, de la conception à la distribution.

Des études sur Lean montrent que la prise en compte des fonctionnalités de Lean dans les phases de conception d'un nouveau système peut conduire à un système optimal dès la phase de conception, et ne nécessite pas l'application des outils de Lean qui sont parfois coûteux, chronophages, et gênants pour les utilisateurs en terme de sécurité de l'utilisateur. Ce qui pourrait conduire à des blocages difficiles à surmonter. En plus, la prise en compte des fonctionnalités Lean dès les premières phases de la conception du système de production pourrait faciliter le développement de l'Industrie 4.0.

Dans cette thèse, nous développons une approche innovante de la conception par l'intégration de Lean dès les phases de conception dans le but de choisir les solutions qui ne garantissent pas seulement une utilisation sûre du système, mais permettent de concevoir des systèmes (machines) fiables, sans gaspillage, rentables, etc.

Nous avons en premier lieu réalisé un sondage pour savoir comment les concepteurs intègrent les conditions d'utilisation dans le processus de conception de leurs systèmes, ensuite nous avons analysé la correspondance entre le Lean et l'Industrie 4.0 pour proposer une méthode qui va avec les occupations actuelles des industriels.

Pour cela, nous avons analysé les fonctionnalités de Lean, les identifié, et les classifié pour déterminer celles qui sont intégrables dans la conception de systèmes de production dans le contexte de l'industrie 4.0. Une démarche « Lean-Système-Design » a été développée. Elle définit un guide systématique et détaillé pour l'intégration de Lean dès les premières phases de conception.

Cette démarche est illustrée par deux exemples pédagogiques. Le premier porte sur le cas de la conception d'un système intelligent de traitement des déchets. Le deuxième évoque le cas du débouchage de la buse d'une imprimante 3D. Une troisième application industrielle a été réalisée en partenariat avec une entreprise sur la conception d'un outil numérique de système de commerce de proximité.

Mots-clés : Lean, conception technique, conception interactive, méthodes de conception, conception inventive, Industrie 4.0, développement durable.

Abstract

Lean is an approach that aims to optimize the overall performance of a production system by applying improvement methods to eliminate waste in the entire industrial process, from design to distribution.

Studies on Lean show that most of the technical and organizational tools and methods developed by engineers and engineering departments aim at improving the overall performance of an existing system in terms of productivity, quality, time-saving, and costs, etc. Therefore, there is no need to implement Lean tools, which are sometimes costly, time-consuming, and disruptive for users in terms of safety, training, and task existence. These can lead to obstacles that are difficult to overcome. Besides, considering Lean functionalities from the early design phases could facilitate the development of Industry 4.0.

In this thesis, we develop an innovative design approach for the integration of Lean from the early design phase to select solutions, that not only guarantee the safe use of the system, but also allow the design of reliable, no waste, and cost-effective systems (machines), etc.

We first surveyed to find out how designers integrate the conditions of use in their system design process. Then, we analyzed the correspondence between Lean and Industry 4.0 to propose a method suited to companies' current activities.

For this purpose, we analyzed, identified, and classified the functionalities of Lean to determine which ones can be integrated from the design phase of production systems in the context of Industry 4.0. A "Lean-System-Design" approach has been developed. It defines a systematic and detailed guide for the integration of Lean from the early design phase.

The approach is illustrated on two pedagogical examples: The first one concerns the case of a smart waste treatment system. The second one concerns the case of a 3D printer clogged nozzle. And a real industrial example in collaboration with a company refers to design a digital tool for convenience stores.

Keywords: Lean, engineering design, interaction design, design methods, inventive design, industry 4.0, Sustainability.

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Chapter 1. Introduction

This chapter aims to present the context and to give a general introduction to this thesis, consisting of the following parts:

- The reception laboratory.
- The general background of the thesis.
- The research problems positioning.
- The research contribution.
- The structure of the manuscript.

1.1. Reception Laboratory (ICube/CSIP)

My thesis is carried out in the CSIP team of ICube laboratory at INSA of Strasbourg, whose research focus is the inventive design and Knowledge management.

The main topic of CSIP focuses on theoretically and practically developing new design methods for products/systems/services that take into account their entire lifecycle, especially at the early stages of design.

The fields of application are to design products, production systems, and information systems.

1.2. General research background

One of the main principles of Industry 4.0 is to associate future users, company management, and design in a structured and in-depth reflection to reach an industrialization model that will allow the best possible compromise between market requirements, service constraints, and industrial performance as soon as possible (Fontanille, Charles, and Fr 2010). According to Eiji Toyoda, there are certainly opportunities to improve the production system (Dennis 2017). Over the years, concepts and methods are developed to improve the performance of the production system (machines, process).

In this context, companies tend to rely on recent technologies to improve their performance by adding new high-tech solutions (John Black and John 2008). These allow them to produce a customized product faster while limiting costs, eliminating waste, and optimizing the workplace.

On the one hand, these systems can be fully automated, and thus, some human tasks can disappear. On the other hand, the role of humans may increase. And, these technologies can use it to perform human tasks efficiently and ergonomically.

Indeed, Lean has an excellent reputation for improving the industrial performance of systems and machines already designed to optimize their performance by eliminating wastes. And, over time, Lean is applied in many other areas. For example, Lean IT in software development, Lean Green, Lean and sustainability, etc.

Thus, in most cases, the designed systems are not optimal and need improvement to increase their performance. So, applying Lean during the use phase can solve the problem. But the application of Lean tools is not always optimal and has drawbacks. Most of these Lean tools require time and budget to be invested for implementing a continuous improvement project either by the company's teams themselves or by calling on Lean experts.

Also, the improvement of the existing system can cause upheavals, which harms the operator, his behavior in the workplace, his interactions with the machine, sometimes makes him uncooperative and seems to be a source of resistance to such a change.

Besides, according to Lean expert Hohmann (2012), Lean worksites focus on local problems or a given area, regardless of the links, interactions, and impacts in other areas, which makes that the improvements are not optimal and does not cover the whole system.

Lean integration from the design phases is a more appropriate solution.

Furthermore, considering Lean requirements from the early stages of production system design could facilitate the development of Industry 4.0.

It should be pointed out that many recent studies affirm that the implementation of new technologies in Industry 4.0 is compatible with Lean principles (Mrugalska & Wyrwicka, 2017) (Uwe Dombrowski, Krenkel, & Richter, 2017).

This thesis aims to propose for the designer a holistic approach to carry out the design work, to improve the performance of the system from the early design phase by taking into account the requirements of Industry 4.0, and by considering Lean functionalities from the design phases.

The proposed approach contributes to design a complex system such as a production system (machine, equipment, user), and service system.

Then we focused the subject to Lean, notably because Lean can meet the performance criteria either alone or by combining Lean with other concepts such as sustainability, and agility, in an Industry 4.0 context

Also, the integration of Lean from the design phases is broad and can concern the system components. To more precisely delimit our approach, we have chosen to start with the mechanical part. The control systems could be considered through the choice of criteria listed in our work.

1.3. Research positioning

The main purpose of Lean Thinking is to eliminate waste in the entire industrial system. As we know, to implement Lean thinking, several tools and methods have been developed. Lean is applied to existing machines to improve their efficiency by eliminating waste in a continuous improvement process. And also, Lean is applied during the design work.

Many studies mentioned in the literature attempt to integrate disciplines, concepts, and criteria during the design phase of the production system to meet the needs of customers and users (quality, quantity, and cost) and to reduce modifications by adding additional procedures to the production process to increase the efficiency. Thus, we could mention the work relating to Design for X: where X can be a safety and ergonomics (Xiaoguang Sun et al. 2018) (Sadeghi et al. 2016) (El Mouayni et al. 2020), cost (Schuh, Kelzenberg, and Wiese 2019), reliability (He et al. 2020), user experience (Renaud et al. 2019), etc.

Various studies have shown that Lean may play a significant role in adding some criteria to the system, such as Reconfigurability (Kant, Pattanaik, and Pandey 2020), Human Factors and Ergonomics (Sakthi Nagaraj et al. 2019), Sustainability (Siegel et al. 2019), and so on.

Lean can be applied from the early design phase in the form of Lean keys performance indicators (D. Mourtzis, Fotia, and Vlachou 2017), or Lean design rules (Jt Black, 2007).

We share the same goal of Lean Design and Design for X. But we seek to avoid their limitations. Design for X works on a specific stage of system or a specific criterion (Uwe Dombrowski, Schmidt, and Schmidtchen 2014). The considered criteria are related to the "X". For example, Design for Cost is intended to help designers to propose a low-cost solution. But, this solution needs to apply some Lean tools such a 5S, SMED, etc. to improve their efficiency in the use phase of the machine or the system.

Also, Lean Design focuses on value-adding activities from the perspective of the end customer, resulting in the elimination of all non-value-adding activities. Accordingly, Lean Design has been considered as a theoretical approach to reduce waste, and It focuses on customer value (C.-H. Ko and Kuo 2015). Lean Design suggests to designers to follow some general rules according to Lean thinking. But detailed information is not provided, especially in the final stages of design, to help designers in their decisions (Uwe Dombrowski, Schmidt, and Schmidtchen 2014).

To precise the position of our contribution, we have analyzed the advantage and limitations of both methods: "Design for X" and "Lean Design".

The results of these analyses are presented in table 1.1.

Table 1.1 Our proposition comparing to the existing methods

Design for X	Our proposition	Lean Design
Systematic approach	Systematic approach	Theoretical approach
X refers to a specific criterion	X cover most of criteria	Based on Lean thinking
Specific stage of product life cycle	Design phases	All stage of product lifecycle
Qualitative design guideline to a specific aspect	Quantitative and qualitative design guideline	Qualitative design guideline
Complex optimization	Optimization of add-Value- functions	Preventing Non add-Value functions
Give a suitable solution for a specific decision according to criteria dependent on X	Resolve the problems of contradictions	Not able to give a suitable solution for any kind of decision

Following the most common types of production systems mentioned in the literature, dedicated production lines (DML) and flexible production systems (FMS) do not meet expectations due to their implementation procedures. DMLs are productive but are difficult to adapt to new products. FMSs are generally less productive, expensive, and difficult to maintain. Industries are moving more and more towards reconfigurable production systems RMS to achieve both the flexible functionality of FMS and the scalable capacity of DMLs (Moghaddam, Houshmand, and Fatahi Valilai 2018) (Battaïa, Dolgui, and Guschinsky 2017). Agile development systems guarantee more flexibility (Qamar, Hall, and Collinson 2018). Accordingly, the new production system design should offer more flexibility and scalable functionality (Azab and Naderi 2015). Besides, DMLs are for specific products. So, the information provided about the products to be manufactured (lead time, takt time) could be considered from the early design phase. On the other side, in the case of FMS and RMS, it is a not-so-obvious topic to take into account the information related to the production and application of Lean from the early design phase. Therefore, we have two cases to consider Lean functionalities from the design phase. The first is for DML and the second for FMS and RMS.

Our proposition about DML and FMS is shown in table 1.2.

Table 1.2 Our study following the evolution of manufacturing paradigms

DML	FMS	Our proposition
Design for X	Design for X	Lean Design
Mass production	Mass customization	Mass customization
Low cost	High cost	Variety of products
Common Product	Product family	Unique product
Mobile assembly line	Numerical control (NC)	Additive Manufacturing
Continuous improvement and application of Lean.	Continuous improvement and application of Lean.	Integration of Lean from the design phase

It is also relevant to point out that our work concerns not only the implementation of production systems, but we focus in particular on the design of a workshop system (Machine, Conveyor, Workstation) or independent machines (3D printer machine, treatment machine, etc.).

1.4. Contributions

Our framework scope is in the same area of Lean Design and Design for X. We seek to identify and integrate Lean functionalities to consider most of the required performance criteria in the context of Industry 4.0.

In this context, many research questions may be raised:

1 Which functionalities of Lean could be considered from the early design phase?

2 How can we help designers to choose solutions that do not breakdown the system?

3 How to solve the contradictions due to the integration of Lean from the design phases?

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

(1) The identification of criteria that depending on Lean and Industry 4.0.

(2) The identification of Lean functionalities fulfilling the required criteria.

It covers how to link the criteria to the Lean functionalities in Industry 4.0 frame.

For each criterion, according to the literature, we have related to the appropriate Lean functionalities.

(3) The method of Lean from the early design phase:

We propose a framework with seven steps to guide designers during the integration of Lean functionalities in the design phases model (conceptual, embodiment, and detail).

(4) The method of resolving contradictions:

We use the inventive design methodology (IDM) based on the "Theory of Inventive Problem Solving" (TRIZ) to help designers identify, resolve contradictions, and provide innovative technical solutions.

1.5. The manuscript structure

In this section, we define the lecture map of this manuscript.

In chapter 1, we have illustrated the general introduction to our research, including the reception laboratory, the research background, the research problems, and the contribution.

In chapter 2, we detail the review of the literature on complex systems, their design methods, and also on the machine and product design. Then, we present the principles, methods, and tools of Lean, as well as their integration in the design phase. The framework of this work is Industry 4.0. For that, we also present its concept, its principles, and its combination with Lean.

In chapter 3, we present our proposed method, which is structured as follows:

(1) In section 1, we present a survey proposed to industrials companies to understand how industrial companies integrate the condition of use from the early design phase, especially the human factors and ergonomics.

(2) In section 2, we present the study of the convergences and contradictions of the implementation of Lean concepts and Industry 4.0 in production systems that may strengthen the premise of considering the Lean and Industry 4.0 requirements during the early stages of production system design.

(3) In section 3, we present our systematic approach Lean-System-Design of integrating Lean functionalities in each phase of the design process.

After presenting our approach in Chapter 4, we illustrate its applicability with two pedagogical examples and then apply it to an industrial case.

The first one is about the design of a smart waste treatment system.

The second one, concerning the clogged nozzle of a "3D" printer, discusses the usefulness of IDM-TRIZ to solve this problem.

And a real example in collaboration with a company concerns the design of a digital tool for convenience stores. This industrial application shows that our proposed approach can also be applied to a service system.

In chapter 5, we present the first steps for the implementation of the proposed Lean-System-Design approach in a module CAD.

In chapter 6, we present the conclusions of this thesis, which contains the contributions and limitations, and the future perspectives of our work.

Figure 1.1 shows the overall structure of our thesis.

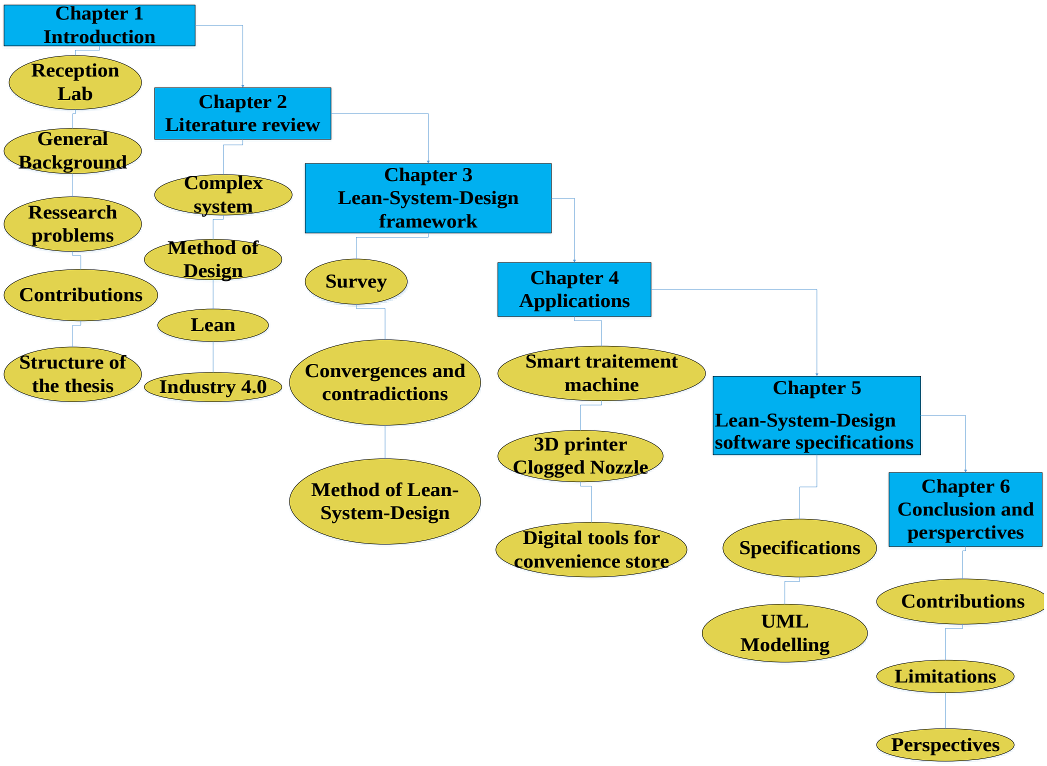

Figure 1.1 Framework of this thesis

Chapter 2. Literature review

2.1. Introduction

In this chapter, we present the state of the art of integrating Lean from the design phases in the context of Industry 4.0. For that, our literature review contains four parts that cover the two concepts: Lean and Industry 4.0, and their implementations from the design stages.

(1) In the first part, we present our complex system. It can be a production system, manufacturing system, machine, or service system, etc.

(2) In the second part, we highlight how the most method of design could be helpful to consider the industrial performance criteria.

(3) In the third part, we present a general introduction on Lean to underline its importance in increasing the performance of a system. Then, we present a review of the literature on Lean integration from the design phases.

(4) In the fourth part, we also present a general introduction of Industry 4.0 to underline its importance on system performance.

Then, we present a review of literature on the convergence and divergence of the two concepts Lean and Industry 4.0.

2.2. Complex system

A system is an organized collection of personnel, machines, and methods required to accomplish a set of specific actions (CIRP 1990). A system can thereby be defined as a ‘‘collection of different components, such for example, people, robot, and machines, which are interrelated in an organized way and work together towards a purposeful goal” (Säfsten and Bellgran 2009). Its complexity may result from the interaction between its components.

A production system is composed of several interdependent sub-systems to satisfy the needs of internal customers (operators) and external customers (customers and suppliers) (Jt Black 2007), which consists of four components:

1) Technical system: Machines, and equipment.
2) Handling system: This includes equipment necessary to ensure the transfer of materials and products between production lines.

3) Human system: Operators, Technical, and management staff.

4) Information system: Computers and software (Säfsten and Bellgran 2009).

According to some authors, (Erlach 2013) (Dombrowski, Uwe Mielke 2015), the two main tasks that should be performed in the production system design works are:

(1) The way of manufacturing to fulfill production and process planning.

(2) Industrialization to plan and organize the activities to design the production system.

In the following section, we present some of the most commonly used design methods.

2.3. Engineering design

The fundamentals activities of engineering design are to find the optimal technical solution which guarantees a set of requirements and constraints related to human, material, technological, economic, and environmental, proposed by Pahl et al. (2007):

- Human (human-machine interaction, the safety of users, etc.)
- Laws and insights of science.
- Previous experiences.
- Physical realization of solution ideas.
- Professional integrity and responsibility of the designer.

According to Chen (K. Z. Chen 1999), the engineering design process consists of two distinct processes:

(1) The creative process: New ideas and solutions are synthesized without referring to previous examples.

(2) The analytical process: The design decisions are made by evaluating the new ideas proposed.

A system must integrate more and more criteria and constraints to meet the market, customer, complexity, and environmental requirements that make it more efficient from the early design phases. Therefore, engineers develop various efficient design methods and processes to carry out the design work, such as Design for X, Reliability Design, Axiomatic Design, TRIZ, etc.

The "X" of "Design for X" generally represents the design criteria that the system (manufacturing, machines, processes) must satisfy first. As we mentioned in the previous chapter, "X" can be "Cost" to mention "Design for Cost", "Production" to mention "Design for Production", "Safety" to mention "Design for Safety", and so on.

The Design for Production provides a comprehensive view of the entire production system, aiming to stay up to date in product development (Maneschi and Melhado 2010). Design for manufacturability is a method to evaluate product design through a performance ratio according to some characteristics and criteria (S. Das and Kanchanapiboon 2011). Saxena et al. (2012) presented a design model for the reconfigurability of the production system design, based on three phases, by considering various characteristics such as multi-product line, machine type, machine configuration, machine placement. Design for Assembly principle aims to reduce the number of parts for minimizing the assembly time, fasteners, parts inventory, and the cost of the products. Design for Maintainability aims to eliminate the waste of repairing time, thus, decreasing the cost of remanufacturing by taking into account the criteria of repair and maintenance (Battaïa et al. 2018). Weisheng Lu et al. (2020) presented a design guideline from the review of the literature of "Design for Manufacture and Assembly" to help designers to optimize the design of the production system by linking the principles of Lean construction with the principles of "Design for Manufacture and assembly". Design for Additive Manufacturing highlights how to design components that take full advantage of these Additive manufacturing technologies (Pradel et al. 2018a). The Design for Environment aims to consider the environmental impact from the early design phase (Andreasen and Olsen 1994). Design for Maintenance is a method to optimize maintenance activities from the design process (Vaneker and Diepen 2016).

Many other methods mentioned in the literature are popular or invented by researchers that aim to enhance the performance of a production system or industrial machinery. For example, Design for Six Sigma describes the use of the steps of the method of Six Sigma in the Engineering design process (Liverani et al. 2019).

The Value Driving Design aims to focus the design solution according to the customer value. Therefore, it provides methods and tools that take the value as a basis of measurement for selecting and evaluating the optimal configuration for the operations and the tasks of the design work (Bertoni et al. 2015).

To enhance the reconfigurability of the production machine, Battaia et al. (2020) developed a mathematical model for the cost optimization problem used for batch production. To increase the efficiency of the machine, Bai et al. (2020) propose an aggregation-based analytical procedure to calculate the performance metrics of serial production lines. Based on the structure of reconfigurable production systems, Gu et al.

(2018) provided a production system architecture for mass-individualized products using conveyors that allow more cost-effective, small-volume, and individualized products.

In the following section, we present the Lean concept and its integration from the design phases.

2.4. Lean

As mentioned in the previous chapter, we propose to integrate Lean functionalities from the design phases to obtain systems that do not require the application of Lean tools to optimize their performance in the use phase. In this section, we present a review of the literature about Lean integration from the design phases. For this reason, it is crucial at the outset to give a general introduction to the concept of Lean, its history, principles, methods, and tools.

The Toyota Production System (TPS) or Lean production is a concept developed by Toyota engineers to eliminate waste of the entire industrial process from design to distribution to improve the process. The main rule on which TPS is based is to reduce the time between the customer's order and shipment as much as possible. Therefore, all types of waste must be eliminated.

To implement Lean thinking, several tools and methods have been developed. Lean is applied to existing machines to improve their efficiency by eliminating waste in a continuous improvement process.

According to Womack (1990), waste is defined as: "the human activity that absorbs resources but does not create value.". And, value is "the capability provided to a customer at the right time at an appropriate price, in each case by the customer".

2.4.1. Lean principles and tools

Taiichi Ohno (1982), considered the "father" of Toyota's production system, identified seven forms of wastes (Muda):

- Muda: Overproduction, waiting time, transport, storage, movement, and production of defective parts.

And two other type of wastes:

- Muri: Physical overload, arduousness, mental stress, etc.
- Mura: Irregularity, uniformity, etc.

Womack (1990), in his book "The Machine That Changed The World" described the five principles of Lean, as shown in Figure 2.1.

(1) Specify Value: Identify what customers want.

(2) Identify the Value Stream: Identify activities that contribute to these values.

(3) Flow: Create continuous work processes without interruptions.

(4) Pull: Produce only in response to customer demand.

(5) Perfection: Generate, test, and implement process refinements of continuous process improvement.

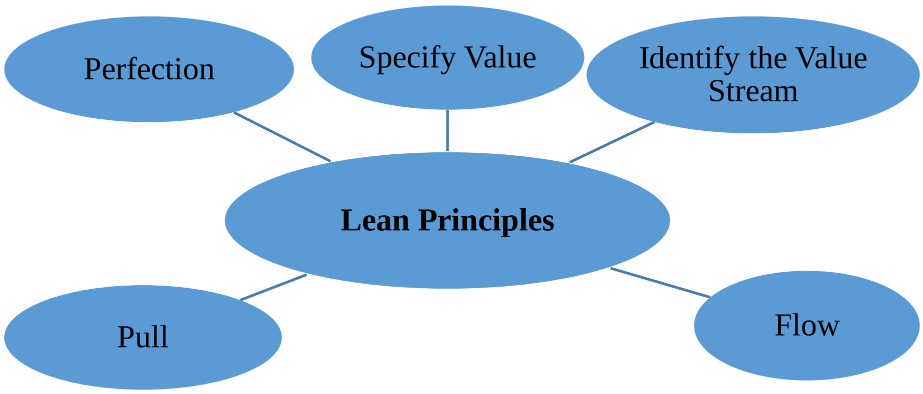

Figure 2.1 Lean principles

In addition to the five principles identified by Womack (1990), there are three other principles (Supplier Integration, Multi-Functional Teams, and Zero Defect) that represent about 60% of the principles identified in the literature (Mirdad et al. 2015).

However, the most famous classification of the most common principles is made by (Lander and Liker 2007), representing the 14 principles of the Toyota model in management and organizational vision, as shown in Figure 2.2.

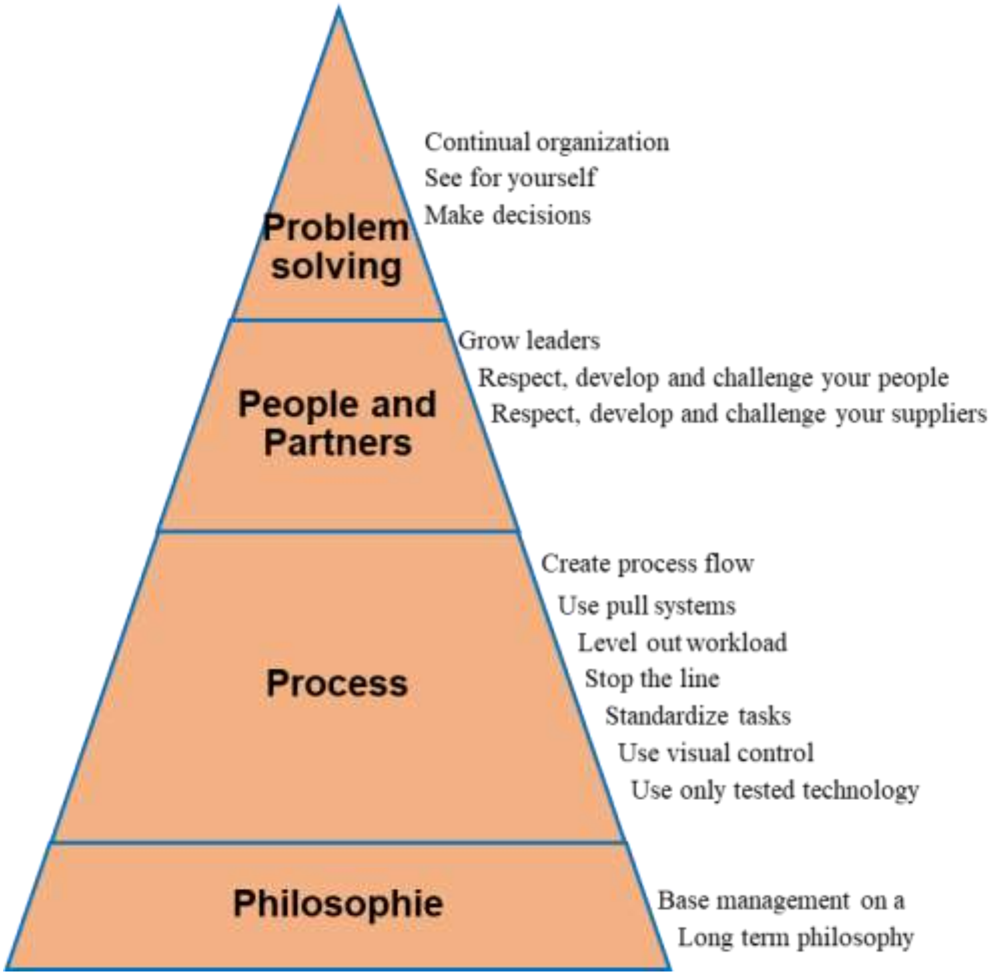

Figure 2.2 Lean Management principles

The famous House of Lean contains tools (Dombrowski, Uwe Mielke 2015) that have been applied originally for manufacturing systems, as presented in Figure 2.3

The first pillar is Jidoka (Automation), introduced as a culture to reduce quality defects and adapt to automatically detect deviations and breakdowns, using some tools and methods such a Poka-Yoke, Andon, etc. (Belekoukias et al. 2014).

The second pillar is Just in Time (JIT) to synchronize the production process by using Kanban. It is production management via a pull system with zero defects, and failure, etc. (Jastia and Kodali 2015).

Kaizen is a continuous improvement strategy for eliminating waste, including some methods and tools such as 5S, run charts, 5 whys, brainstorming, data check sheets, Pareto chart, Gantt chart, mistake proofing, and process mapping (Garza-Reyes et al. 2018). To decrease the quality losses, according to the Japanese institute, the Total Productive Maintenance (TPM) is a maintenance system, which covers the entire life of the equipment, including planning, manufacturing, and maintenance, and involves all employees from production and maintenance personnel to the management staff (Jeon et al. 2011). TPM aims to reduce the six big losses (breakdowns, setup and adjustment time, idling and minor stops, and speed). The main tools associated with TPM are Overall Equipment Effectiveness, Single minute exchange of die (SMED), 5S, Autonomous Maintenance, Planned Maintenance, and Quality maintenance. The value stream serves to clarify and visualize the process, including the flow of material and information for the manufacturing system to underline wastes and enable their elimination (Andreadis, Garza-Reyes, and Kumar 2017).

Figure 2.3 House of Lean

Among the tools most implemented by the companies is The 5S approach provides some famous steps: Sort, Set in Order, Shining, Standardize and Sustain to enable improvements in the workplace, thus improving quality and safety of operator and efficiency, and reducing time, waste, and sources of error (Delisle and Freiberg 2014).

SMED is an organizational and technical methodology that aims to reduce changeover times (set-up time) to less than 10 minutes (Thierry Leconte 2008). It increases the flexibility of the production machines to reduce the inventory by enhancing the efficiency by reducing the downtime of production machines. SMED contains four phases: SMED contains four phases: 1) The first phase is to identify all tasks. 2) The second phase serves to classify operation into internal operations that require the stop of the machine, and external operation, which can perform while the system runs.

3) The third phase concerns the conversion of internal into external operations and to standardize. 4) The latest phase is to streamline all operations to adapt to a more efficient solution (Braglia et al. 2016). Heijunka is a method, which serves for leveling production (Arunagiri and Gnanavelbabu 2014). Using Kanban in the pull system to smooth the production according to customer demands guarantees various products and more agility (Weizhuo Lu et al. 2011). Poka-yoke serves to improve the visibility of operators and limit these choices to perform a task in a way that the right choice is the only possible to prevent failure (Grout and Toussaint 2010).

Over time, these tools have become known in many other areas, related to the improvement of the production systems to increase the performance of all these components (machines, human, equipment, and process and software), and also to consider the environment and customer and supplier integration.

Lean also applied to other fields. In the environmental field, Carvajal-Arango et al. (2019) highlight the effect of the application of Lean methods and tools on the three dimensions of sustainability: environmental, economic, and social. Incorporating Lean to Green concepts defines approaches to manage organizations and their supply chains to improve organizational and sustainable performance. These enable to eliminate environmental waste related to water, energy, air, solid and hazardous waste (Bhattacharya et al. 2019). Farias et al. (2019) provide a list of many criteria and sub-criteria related to Lean and Green performance. By linking Lean, Agile, and Green principles, Udokporo et al. (2020) present a decision-support framework containing more than 40 principles and practices to enhance the product performance in each life cycle stage.

To enhance process and software, Wang et al. show that Lean can be applied in agile software development (X. Wang, Conboy, and Cawley 2012). Soltan et al. (2015) show that combining Lean to Agile concepts can increase the competitiveness and the productivity of companies. Thus, it enhances the company's profits. Nurdiani et al. (2016) present 13 Agile and Lean practices, incorporating Lean in software development.

Lean is applied in many other sectors such as "Lean Hospitality" to describe the application of Lean in the Hotel Sector (Rauch et al. 2016), "Lean Construction" to place Lean in engineering construction (Pasquire 2012), "Lean Healthcare" to use lean thinking for improving medicines and hospitals (Jordon et al. 2019) (Akmal, Greatbanks, and Foote 2020) (Compère et al. 2019), "Lean Logistic" (Frontoni et al. 2020), and "Lean-Startup" (Felin et al. 2020) (Jesemann et al. 2020), etc.

In the following, we focus on Lean in Engineering design.

2.4.2. Lean in Engineering Design

As mentioned in the previous chapter, Lean integration from the design phase could be an increasingly appropriate solution to improve overall system performance and to optimize the interdependencies between their components. The operator can perform his tasks without losing time in optimal workplace conditions, enhancing safety, teamwork, and usability. The machines will be designed to perform tasks in an optimal, cost-effective, and ecological way. As we have shown previously, many design methods have been developed to help designers to satisfy the constraints and requirements by designing a performant system. We share the same goal of these methods, but by following Lean thinking.

2.4.2.1. Lean Design

Lean can be applied from the early design phase in the form of keys performance indicators (KPIs) or Lean design rules.

"Lean rules are a set of explicit rules based on the lean theory, principles and practices (lean tools), concerning the entire product/service lifecycle, aiming to waste elimination, profit amplification, and stakeholders satisfaction" (Mourtzis et al. 2016).

Black et al. (2007) provide some Lean design rules to explain how Toyota changed the final assembly lines into a mixed-mode, and the linear subassembly lines into U-shaped:

(1) The first design rule means that the final assembly line (FA) should be respected Takt time (TT), based on the daily demand.

(2) The second design rule is that the subassembly manufacturing must be redesigned into parallel lines or U-shaped assembly cells to follow the method of production one-piece flow.

(3) The third design rule is that the processing time for any part of any machine in the manufacturing system is less than the necessary cycle time (NCT).

(4) The fourth design rule is that production management follows a pull system, using Kanban to give production orders.

To reduce waste of Product-Service-System (PSS) lifecycle phases, Mourtzis et al. (2017) used the Key performance indicators (KPIs) with Lean principles to provide the Total Leanness Index (TLI), decreasing energy consumption and providing efficient maintenance.

The combination of Lean thinking with Design for Six Sigma, who called Design for Lean Six Sigma, is significant to provide a global and complete method to satisfy all requirements (Jugulum and Samuel 2010).

2.4.2.2. Lean Product Development, Lean Production development, Lean Product-Service development

Lean Product development (LPD), as the name indicates, is some of the Lean principles, methods, and tools, implemented to minimize waste and improve the product development process (Tortorella et al. 2016). LPD is the application of Lean Thinking to the product development process to meet innovation requests (Pessôa et al. 2017). Hoppmann (2011) claims that LPD is based on five major principles: 1) Value focus, 2) Entrepreneur system designer, 3) Concurrent engineering, 4) Cadence, flow, and pull, and 5) Team of responsible experts. Dombrowski et al. (2017) put seven principles for LPD to avoid wastes: 1) Kaizen, 2) Standardization, 3) Visualization, 4) Flow and pull 5) Zero defects, 6) Employees and Leadership, and 7) Front Loading. Marodin et al. (2018) underline the most practice of LPD: 1) Concurrent Engineering approach to the design of products. 2)Modularization and standardization of the product structure to be standardized and used across product lines Design, 3) Design for Manufacturability by simplifying designing products to be easy to manufacture, 4) Customer involvement in product development aligns product specifications to the customers' need.

To satisfy the Industry 4.0 requirement, using Axiomatic Design (AD) matrix, Rauch et al. combine the Lean principles and Industry 4.0 with Lean Product Development (LPD) to introduce a new notion of Smart Product Development (Rauch et al. 2016).

In the same way, Lean production development aims to integrate Lean thinking from the early design phase to design an effective production system based on Lean principles (Lindskog et al. 2016). De Kogel et al. (2016) provide a Lean design support tool to enhance the performance of the production system from the design phase.

Moreover, another notion, which is fundamental to define it in our research, is the Product-service system (PSS). PSS defines the integration of business models, products, and services together throughout the lifecycle stages, creating innovative value add for the system; and delivering value in use (Trevisan et al. 2017). Product-Service-System design aims to provide more sustainable and ecological solutions for the industrial company by putting the customer in the center of the product-service system design (Aurich et al. 2006).

According to Mourtzis et al. (2016), the PSS design process contains three phases:

(1) Customer analysis: Designers collect data to identify customer needs.

(2) PSS conceptual design: Designer with the engineering team generates ideas.

(3) PSS detailed design: Designer transform ideas into detailed solutions (Akasaka et al. 2012).

To integrate the servitization aspect, Lean Product Service Systems (LPSS) use Lean tools and add inter-connected and embedded technologies, which have an extremely positive effect on product lifecycle, customer satisfaction, and the environment (Sassanelli et al. 2015). Lean-Product-Service development (LPSD) focuses on delivering the highest value to the customer by increasing efficiency and reducing waste, with a strong focus on the managerial aspects of the product and service development process.

2.4.2.3. Lean Construction

Another concept to describe the implementation of Lean principles from the design phase is the "Lean Construction". Lean Construction aims to design production systems with minimum waste of materials, time, effort, and the maximum value (Aziz and Hafez 2013). This helps designers to optimize the production system construction by understanding what kinds of inefficient operations must be avoided. But some criteria, depending on the human-machine interaction, are not as strongly solicited in Lean Construction (Green and May 2005), (Weisheng Lu et al. 2020).

2.4.2.4. Lean and TRIZ

Integration of all performance criteria related to the number of functions and constraints that the designer has to find a solution that fulfills and respects all of them. In this case, the designer could not propose a performant solution because the set of solutions could become very small and perhaps equal to zero. So, he has to use inventive design methods like Brainstorming or Axiomatic design, or the "Theory of inventive problem solving" (TRIZ). These methods are useful in this part to solve the design problem when the classical methods cannot give a fulfilling all criteria. Because of that, our laboratory is the leader in France in research on TRIZ. We adopt this method for the case where finding a solution requires inventive design. So, in the following, we present this method.

TRIZ provides a set of technical methods and tools to search the optimal solutions like contradictions matrix, separation principles, standard solutions, etc. Figure 2.4 illustrates the different steps of TRIZ. As this figure shows, the designer should first formulate the generic problem. For this purpose, they could apply one of several tools like function analysis, problem graph, and nine screens, etc. In the next step, it is essential to use one of the tools such as "Contradiction Matrix", "76 inventive

Standards", "ARIZ", etc., to transform the generic problems into generic solutions. At the end of the process, it is possible to create specific solutions related to the initial problem (Starovoytova 2015).

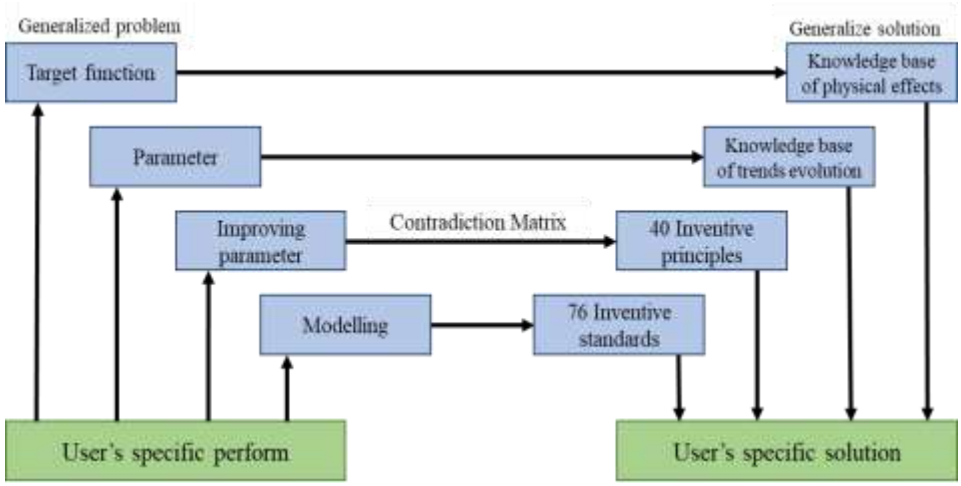

Figure 2.4 Contributions of TRIZ (Revised from Nakagawa (2011))

The integration of Lean functionalities from the early design phase could be a source of some contradictions related to various reasons such as system performances and user considerations. Using TRIZ can help designers to resolve major contradictions that can arise and also find appropriate solutions.

For example, when we consider the functionalities of SMED from the design phase to remove an internal into an external operation, we ask the user to make a setting-up operation when the machine runs or with minimum time. So, the operator may not be safe. The contradictions here are between productivity and user safety. These contradictions could be solved using TRIZ.

Many studies mentioned in the literature highlight the use of TRIZ on the integration of Lean thinking from the design phases to enhance the global performance of production systems. According to these authors, the use of TRIZ to integrate some requirements and criteria could be useful for the designer to choose the most optimal solutions.

Harrington (2017) proposed an inventive method to improve or modify the design by combining Lean and TRIZ. His approach (LTM) is the derivation of the TRIZ 39 × 39 contradiction matrix. The LTM uses a "41 × 3 " matrix in that the three parameters are: quality, cost, and productivity. Based on TRIZ tools, Vaneker et al. (2016) developed a roadmap, helping to solve maintenance problems and to find innovative solutions to their problems. Besides, Guio et al. (2017) provided a general context for the use of TRIZ in Green Supply Chain (GSC) problems. Based on the task decomposition, a new

TRIZ-PSN (Problem Solution Network) methodology has also been proposed by Fiorineschi et al. (2018) to support the designer when faced with a generic problem to reduce the impact of the design change on the product life cycle. Therefore, the designer can choose one of the TRIZ tools to solve the issues that may arise when selecting the optimized solution by resolving contradictions that may result.

Based on Axiomatic Design (AD) and TRIZ, to increase usability during the product design, Uang et al. (2011) intended to analyze and transform customer needs into functional requirements (FRs) and design parameters (DPs). Moreover, using the 39 features, the 40 inventive principles, and the contradiction matrix of TRIZ, Filippi et al. (2015) developed an approach to integrate the requirements of the interaction design. Furthermore, Sun et al. (2016) focused on resolving contradictions that can appear by considering from the early design phase of product design the user requirements in addition to the functional requirements.

Navas et al. (2015) showed that using both TRIZ and Lean methodologies enables enterprises to manage their products through their lifecycles more efficiently, which provides better management of product end-of-life and recycling. Accordingly, Costa et al. (2015) proved that using some tools of TRIZ to implement Lean in the Textile and Clothing Industry to eliminate waste provides the agility of the system and attends to customer's demand. Further, Wang et al. (2017) highlighted the usefulness of the combination of Lean Six Sigma and TRIZ to reduce waste and costs in a savings bank company to improve process performance. Their project consists of four steps: 1) Develop solutions using TRIZ, 2) Implement an improvement plan, 3) Identify the new process capability, and 4) discover system failure.

Toivonen et al. (2015) improved the Toyota Kata Continuous Improvement Method, which defines objectives, problem-solving, coaching, and management, by adding TRIZ techniques to the method.

There are many other examples like this that one can give, could be established the relation between the Lean Thinking principles and TRIZ methodology in terms of increasing system performance and eliminating waste of existing systems.

In the following section, we present a review of the literature on the other concept of our study: "Industry 4.0", representing the context and the perspective of our research field. On the one hand, to highlight the integration of the new technology in the production system. On the other hand, to study the link between the two concepts, Lean and Industry 4.0.

2.5. Industry 4.0

As we mentioned earlier, our work is in line with current trends in Industry 4.0, which is one of the driving forces behind the evolution of production is the evolution of customer demand over time.

Under "Industry 4.0", we mean the beginning of the fourth industrial revolution after mechanization, industrialization, and automation (Figure 2.5). It is the vision of automated smart factories, in which operators, the production system, products, and customers are connected in cyber-physical systems (Karre et al. 2017). These are technical systems in which networked computers and robots interact with the real world to connect physical objects.

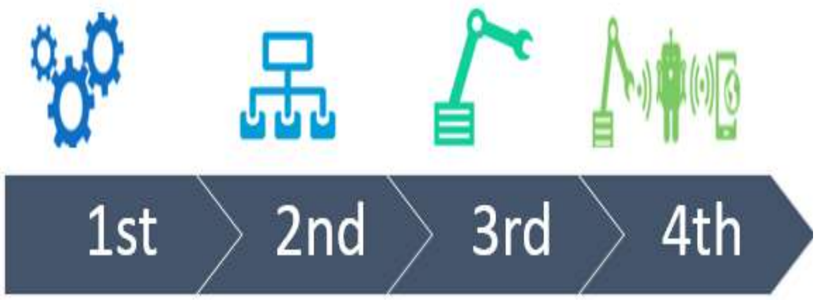

Figure 2.5 Industrial revolutions and future view

The term "Industry 4.0" was invented at the Hanover Fair in Germany in 2011 to describe how these technologies will revolutionize organizations (Radziwill 2018). The Fourth Industrial Revolution is the "Smart Factories", creating a world in which virtual and physical manufacturing systems can co-operate globally with each other in a flexible way, which allows for product customization and the creation of new business models.

Similar approaches have been launched in various industrial countries around the world, such as "China 2025", which aims to improve industrial capacity through innovation-driven manufacturing and optimize the structure of the Chinese industry by training humans for clean production (Li 2017). Other countries such as the United States and the United Kingdom already have a very broad vision of the industry of the future.

In Brazil, the adoption of Industry 4.0 technologies has been seen as a strategy to improve product quality and make manufacturing processes more efficient (Tortorella and Fettermann 2017).

In France, the expression "Industry of the future" launched in 2013 aims to catch up with French manufacturers in terms of production system innovation (Bidet-Mayer 2016). In this environment, production systems need new performant systems and machines to improve production processes and to add value to the concept of Industry 4.0.

2.5.1. Industry 4.0 principles and technologies

Sung, T. K. (2017) claims that the digitization of the manufacturing sector is driven by four disturbances:

(1) The huge increase in data.

(2) The power of calculation and connectivity.

(3) The emergence of analytic and intelligence capabilities and new forms of human-machine interaction such as tactile interfaces and augmented reality systems.

(4) Improvements in the transfer of digital instructions to the physical world.

In this context, the main components of Industry 4.0 are:

Cyber-Physical systems

Cyber-physical systems are physical, biological, and technical systems whose operations are monitored and controlled by a computing system. Computing is deeply embedded in every physical component, possibly even into materials. The computational core is an embedded system, usually demands a real-time response, and is most often distributed (Elhoone et al. 2020).

It is a mechanism controlled by computing entities that collaborate with sensors and actuators to collect the data of the procedure according to a set of defined rules. Thus, it can provide interaction between the physical and computing components (Oliff and Liu 2017). Through the Cyber-Physical systems (CPS), Industry 4.0 can react autonomously. It is self-adaptable and agile. The use of such systems in production is then often described as Cyber-Physical Production Systems (CPPS).

Internet of things (IOT)

IoT is an information network of physical objects (sensors, machines, etc.) that allows devices to communicate and interact and connect using standard technologies with centralized controllers (Kiel, Arnold, and Voigt 2017). The IoT involves the integration of CPS, which connects the physical and the virtual worlds into industrial processes. It also decentralizes analytics and decision making, enabling real-time. It also decentralizes analytics and decision-making, enabling real-time responses (Rüßmann et al. 2015).

Internet of Services (IoS):

IoS allows service providers to offer their services via the Internet. Cyber-Physical Production Systems are generally very complex, consisting of a combination of information technology and software with mechanical and electronic parts that communicate with each other. In this environment, CPSs communicate and cooperate and with humans in real-time and via the IoS. In this way, both internal and cross-organizational services are offered and used by the participants of the value chain (Cohen, Faccio, and Elaluf 2019).

Smart factory:

Based on CPS and IoT, Smart Factory can be defined as a factory where CPS communicate over the IoT and assist users and machines in the execution of their tasks (Hermann, Pentek, and Otto 2015).

Hoffmann (2017) illustrates that the smart factory is defined as follows:

- Products and services are connected via the internet.
- Digital connectivity enables an automated and self-optimized production of products and services without human interventions.
- The decentralization of value networks.

Therefore, a Smart Factory contains technologies that provide the optimum methods and techniques for the production system (Jeschke et al. 2016) (Figure 2.6).

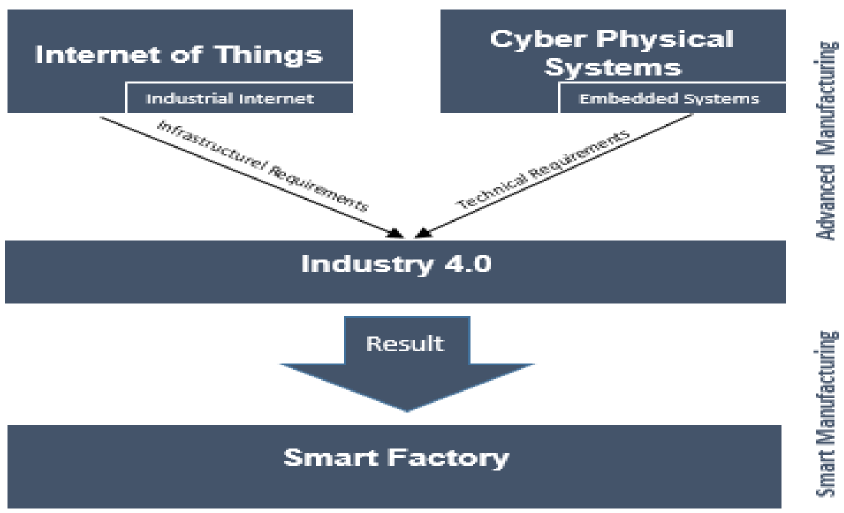

Figure 2.6 Key terms in advanced manufacturing (Jeschke et al. 2016)

To make this Smart Factory, industry 4.0 builds on six main principles. Besides, these design principles make the plant autonomous, flexible, and adaptable to changes in production (Figure 2.7).

Interoperability is a characteristic of a production system in which its components can exchange information among themselves (Liao et al. 2017). Smart Factory is virtualized to be able to simulate and follow in 3D products and production processes. Decisions are decentralized via cyber-physical systems, which make decisions autonomous, and in real-time.

Recent advances in service-oriented computing and cloud computing, including computational power, storage, and networking, offer exciting opportunities for solving complex problems (Bessis, Zhai, and Sotiriadis 2018). Modularity lies in the plant's ability to adapt quickly to a changing demand, which increases the flexibility of the production system.

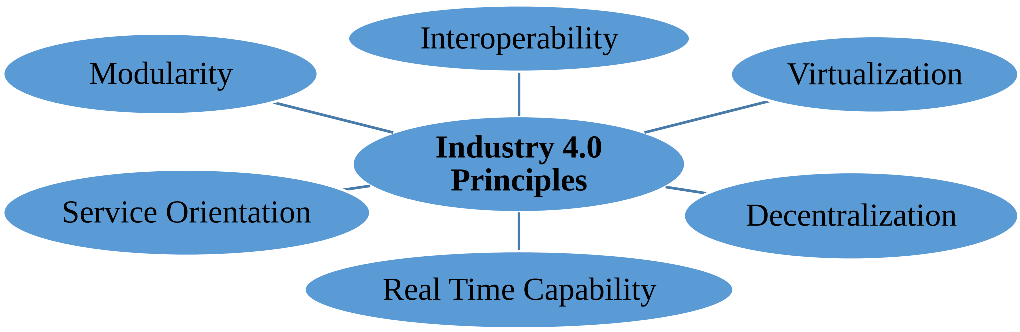

Figure 2.7 Industry 4.0 Design Principles (Slim, Rémy, and Amadou 2018)

In this environment, smart Factories need new technologies to enhance production processes and to aim for value-adds to the concept of Industry 4.0.

The nine famous appropriate technologies, as shown in Figure 2.8, and considering as the pillars of this concept, are integrated along these three dimensions:

(1) The technical system: processes and tools.

(2) The management system: organization, IT, performance management.

(3) The people system: capabilities and behaviors.

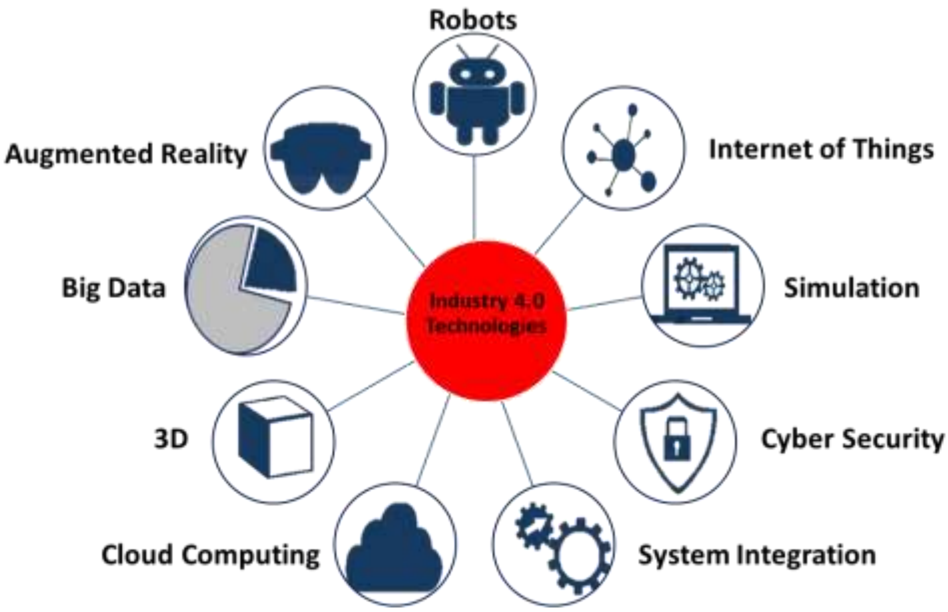

Figure 2.8 Technologies of Industry 4.0 (Laudante 2017)

In this context, Virtual models of manufactured products are essential to bridge the gap between design and manufacturing (Schleich et al. 2017), enabling simulation, testing, and optimization in a virtual environment. Integration and agility in industrial automation need to improve to connect the company with the outside (suppliers and customers).

2.5.2. Industry 4.0 and performance criteria

A production system should be efficient, flexible, reconfigurable that can quickly change its structure, and agile in terms of the volume of production (Long, Zeiler, and Bertsche 2017). Therefore, flexibility is the basis of production systems in Industry 4.0 to realize the individualization of products (Zawadzki and Zywicki 2016). Industry 4.0 focuses on improving competitiveness by reducing costs and increasing the flexibility of decentralized production systems to deliver customized products, which is an advantage to satisfy customer markets (Meissner, Ilsen, and Aurich 2017), involving a small lot sizes and a large number of varieties.

Based on a literature review, Kamble et al. (2018) claim that the integration of Industry 4.0 technologies through the cybernetic interaction of connecting elements and process innovation enables more flexibility, safety in the workplace, and healthier for operators, and improves industrial sustainability performance by designing a machine, which optimizes the three economic, social, and environmental dimensions. Also, Kumar et al. (2018) show that the new technologies of Industry 4.0 could enhance the production systems performance by increasing productivity, automation, human-machine interaction, and machine-to-machine communications and decreasing downtime, inventory, maintenance, and quality costs of production.

The production system is smart in all its components, humans (operators and staff), Processes and software, machines and equipment, building and structure, transport and logistics, customers, and suppliers (Osterrieder, Budde, and Friedli 2020). Through the algorithms of artificial intelligence and IoT, the machines are smart, more autonomous, connected with its engineering staff, able to do self-maintenance, or help the operator to react correctly (Kurth et al. 2019) (Bokrantz et al. 2020).

The smart machine is reconfigurable, flexible, autonomous by tracking progress and connecting data via Radio-frequency identification (RFID) technology. It can warn the operator in real-time in case of failure (Poka-yoke). It is possible to reduce the set-up times to less than 10 minutes by using the Plug'n Produce technology, which increases flexibility (Mrugalska and Wyrwicka 2017).

An Operator 4.0 is smart, autonomous, and connected, having all the necessary information in real-time for his tasks. They are equipped with all new technologies that make their work efficient, useful, and ergonomically (Zolotová et al. 2020). Malik et al. (2019) emphasize that humans still at the center of this digitalization revolution. And so, the vast amount of digital technology serves to enhance human-skills, not to eliminate his role.

Smart products are autonomous, can be controlled by the system, the operators, and the customers. They contain all information about the production, shipping date, and defects, failure, or errors that can happen in real-time. This could facilitate maintenance and ensures customer trust and satisfaction (Rauch, Dallasega, and Matt 2016).

Technologies of smart factories guarantee more software agility that monitors performance and detects changing conditions, which support the management decisions (Lopez et al. 2018). Smart grid (SG) allows energy utilities to control energy transmission in a smarter, efficient, and sustainable way (Faheem et al. 2018).

Accordingly, as we will show in the next section, associating Lean to Industry 4.0 could enhance industrial performance. Davis et al. (2020) affirm that combining the Lean Production System (LPS) with Industry 4.0 can enhance the flexibility, efficiency, and usability of the production machines with less complexity. Also, Leon et al. (2020) prove that associating Lean and Green (L&G) with Industry 4.0 elements increases industrial sustainability performance at a minimum investment cost. Lean and Green (L&G) and the technologies of Industry 4.0, such as blockchains, cloud computing, and big data, can be useful together to integrate the user and customer experiences that positively impact product development, innovation, and user and customer satisfaction (De Giovanni and Cariola 2020).

2.5.3. Lean and Industry 4.0: convergences and contradictions

The elimination of waste requires new technologies, new systems, new processes, etc. Most of the engineering departments of major international companies have developed concrete solutions for a successful implementation of Industry 4.0 in line with the principles and concepts of Lean, on the side of plant improvement through the integration of recent technologies, and on the side of the organization and human-machine interaction, to meet customer requirements and improve performance.

In this context, many questions may be raised:

- Are Lean and I4.0 compatible?
- Lean should it be combined with I4.0?
- Is industry I4.0 a contradiction of lean?
- Will we go towards complete automation?
- Where is the role of the human in this environment?

Many concrete examples mentioned in the literature show the possibility of such convergence between Lean tools with Industry 4.0 technologies.

Dombrowski et al. (2017) try to answer some of these questions by asking 260 German industries to make a detailed analysis of the interdependencies between Lean and Industry 4.0. These studies show that the application of modern information and communication technologies in Lean can improve the production systems performance by obtaining more efficient production and logistics processes.

Sanders et al. (2016) give for each Lean dimension a solution provided by Industry 4.0 to promote the implementation of Lean. Via sensors that make products smart, connected to the operator machinery and equipment, the operators can be alerted in case of failure or defects by detecting the anomaly (self-maintenance). Also, using electronic Kanban to the products can provide the necessary information for the production, which allows receiving the requirements of customers or suppliers in real-time (Kolberg and Zühlke 2015). Accompanied by robots, which work autonomously with humans, and the augmented reality technology, the operator, will be smart, can obtain all the information on the process and product in real-time.

In a reverse way, from analyzing literature, between 2011 and 2018, Bittencourt (2019) conclude that Lean can be a facilitator agent for the implementation of Industry 4.0.

In another dimension of Lean, Sony et al. (2018) underline the implementation of Lean Management and Industry 4.0 by proposing a theoretical guideline based on 15 research propositions, which can be applied, for three types of integration: vertical, horizontal, and end-to-end engineering.

Based on a review of the literature, Rosin et al. (2020) analyzed the impacts of Industry 4.0 technologies on Lean principles. They find that Lean practices relating to Just in Time and Jidoka are the more enhanced Lean principles, while the least enhanced are those related to the waste Reduction, people, and teamwork principles. Given these results, Industry 4.0 does not displace Lean management principles but can strengthen the performance of these principles.

To answer this question: "How can organizations effectively integrate Lean Six Sigma techniques with Industry 4.0 technologies for optimizing performance?" Chiarini et al. (2020) have interviewed Italian manufacturing managers in ten case companies to practice the integration between Lean Six Sigma tools and principles and Industry 4.0 technologies for achieving horizontal, vertical, and the end to end integration of the manufacturing operations and its supply chain. Also, Titmarsh et al. (2020) affirm that the combination of Industry 4.0 is very crucial to enhance sustainable industrial performance. An analysis of the literature review shows that Lean and Industry 4.0 can combine to help Small a Medium Scall Enterprises (SMEs) in their digital transformation (Kolla, Minufekr, and Plapper 2019). This study illustrates that Industry 4.0 is applied not only in manufacturing systems but also in all other areas of complex systems.

2.6. Discussion

According to this review of the literature about Lean in design, we conclude that many of the design methods, which have developed by researchers, aim to link design methods together or with Lean thinking to make them more efficient, to simplify the work of design in searching for the optimal solutions. We share the same goals of these design methods for integrating Lean from the design phases to design a performant system. Most of the methods mentioned in the literature are: either theoretical, based on Lean thinking, but they are not detailed enough to cover all performance criteria and appropriate functionalities, or they focus on one phase of a system's life cycle more than another.

For example, Lean Construction is intended more to Lean in construction than in design. And Lean Product development and Lean Production Development are aimed more at improving the product design process and improving the product over its entire life cycle, including the design phases.

Additionally, this literature review did not attempt to show in detail the limitations of these design methods. Instead, we want to emphasize that the integration of Lean from design is an important and widely known topic in the Lean field to make the system performant and clean from the early design phase.

We aim to develop a more systematic approach and a complete method for integrating Lean from the design phase, covering the interactions between agents in production systems. This approach should also apply to a service system in an Industry 4.0 context.

Few studies show the distribution of Lean following the design phases (Conceptual, Embodiment, Detailed).

Table 2.1 summarizes the most type of Lean in Design and the effects of some Lean interventions.

Table 2.2 presents the majority of Lean methods and practices mentioned in the literature related to Lean tools and Lean functionalities. These methods and practices, derived from the five principles of Lean Thinking and the 14 principles of Lean Management, cover several Lean areas such as Lean Production, Lean and Green, Lean and Six Sigma, Lean and Agile, and Lean 4.0.

We define for each Lean principle: the concerned criteria, the appropriate Lean tools, and the identified functionalities that these tools fulfill to improve system performance.

Table 2.1 Lean intervention from the design phases

Lean paradigms	**Stage of Lean in the design phase**				**Lean aspects**							
	Conceptual	**Embodiment**	**Detailed**	**Use phase**	**Human**	**Human-Robot**	**Organizational**	**Machine to Machine**	**User integration**	**Customer and supplier integration**	**Environment**	**I4.0 tools**
LD	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	
LPD	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
LT	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	
DFS	✓	✓	✓		✓	✓	✓	✓				
Lean				✓		✓	✓	✓	✓	✓	✓	✓

LD : Lean Design

LPD : Lean Product Development

Lean and TRIZ : Lean and Theory of inventive problem solving

DFSS Design for Lean Six Sigma

Table 2.2 Lean functionalities from different Lean paradigms

Lean Paradigm	Lean principles	Lean tools	Lean functionalities	Criterion	References
Lean Management	Long term philosophy	Training Brainstorming	- Base your management decisions on a long-term philosophy.	Innovation Cost	(Krijnen 2007)
	Continuous Flow	One-piece flow Cellular manufacturing Model-U	- Create a continuous flow process.	Productivity	(Mukhopadhyay and Nandi 2000) (Wikner 2018)
		Quick changeover SMED	- Reduce changeover time. - Minimize adjustments. - Standardize operations.	Flexibility Cost Autonomous	(Braglia, Frosolini, and Gallo 2016)
		Total productive maintenance OEE Mistake proofing SMED 5S Autonomous maintenance	- Reduce the six big losses. - Reduce quality losses. - Improve manufacturing equipment efficiency by improving the overall manufacturing performance. - Improve Human performance tasks. - Improve safety and workspace.	Productivity Availability Quality Cost Maintainability Reliability Safety	(Mostafa et al. 2015) (Grout and Toussaint 2010)
	Pull	Kanban	- Produce what the costumers order only. - Apply a communication. between the agents (supplier, process, client). - Produce Just in time.	Speed Communication Productivity Processing	(Prakash and Chin 2014)
	Work loud (HEIJUNKA)	VSM Kanban Training	- Smooth production by volume and product mix. - Remove the waste of Mura or unevenness. - Produce in small-lot.	Customer satisfaction Productivity	(Rahman, Sharif, and Esa 2013)
	Automation (JIDOKA)	Andon Poka-Yoke	- Make problem visible.	Automation Safety	(Abdulmalek, Rajgopal, and

		Mistake proofing	- Stop system when there is an abnormality or problems. - Alert operators in case of problems. - Avoid Human errors. - Find the root cause of problems.	Reliability Maintainability Availability	Needy 2006) (Grout and Toussaint 2010) (Antonelli and Stadnicka 2016)
		Total quality management (TQM)	- Increase the quality. - Improve the final product.	Quality Customer satisfaction Innovation Usability: User satisfaction	(Hafeez, Malak, and Abdelmeguid 2006) (Prajogo and Brown 2004) (Ju et al. 2006)
	Standardization	TPM 5S	- Maintain the regular output of the process. - Maintain the regular timing.	Standard Cost Quality Safety	(Wiengarten et al. 2017; Chiarini and Vagnoni 2020)
	Visual Management (MEIRUKA)	Visual indicator	- Clarify waste. - Detect the anomaly. - Make indicators visible. - Improve information visibility.	Communication	(Grout and Toussaint 2010) (Bevilacqua, Ciarapica, and Paciarotti 2015)
	Reliable technology	Industry 4.0 tools	- Use technology to support people. - Encourage people to consider new technologies.	Reliability Agility Complexity Safety Human skills 4.0	(Stadnicka and Antonelli 2019) (Hoellthaler et al. 2020)
	Leadership	Training	- Grow Leader from the system. - Teach employees.	Human skills Team work	(van Assen 2018; Laureani and Antony 2019; Seidel et al. 2019)
	Human skills (HITOZUKIRI)	Training Cross functional	- Involve Human Skills. - Promote operator's contribution.	Human skills 4.0 Team work Multi skills work Safety	(Malik and Bilberg 2019)

	Partner and supplier	Good collaboration contract	- Respect for your partners and suppliers.	Supplier integration	(Uwe Dombrowski and Karl 2017)
	Go see for yourself (GENSHI GENBETSU)	Work control	- Engineers go to observe processes. - Find solutions.	Leadership skills	(Seidel et al. 2019)
	Make decisions (NEMAWAHI)	Decision making tools	- Consider all the options and agents of system before making decision.	Leadership skills Team work	(Liu et al. 2013)
	Continuous improvement (KAIZEN)	5S Brainstorming Five whys VSM Hoshin Kanri	- Improve the housekeeping. - Improve the process continuously. - Improve the standard. - Eliminate waste. - Improve Human skills.	Team work Innovation Availability Usability Accessibility Safety and ergonomics Cleanliness User satisfaction	(J. C. Chen, Li, and Shady 2010) (Lizarelli, Toledo, and Alliprandini 2019)
Lean And Six Sigma	Prcocess Mapping Seven Quality Standardized Mistake Proofing	DMAIC PARETO ISHIKAWA PROJECT CHARTER 5 WHY	- Eliminate the cause of defects. - Eliminate Waste. - Eliminate Non Value Add activities. - Reduce Cycle time.	Cost Quality Reliability	(Drohomeretski et al. 2014)
Lean and Agile	Customer requirements Competitive intensity Continuous improvement Automation Rapid prototype technologies Decentralized decision making Short development cycle times Culture of learning	SMED Hoshin Kanri Standard Cross functional teams	- Enhance the variety of production. - Enhance the effectiveness response to the customer change needs. - Reduce Lead time. - Apply skills from different company functions from experts.	Flexibility Speed Agility Automation Complexity Smart tools 4.0	(Cagliano, Caniato, and Spina 2004) (Rosário Cabrita et al. 2016) (Sohi et al. 2016) (Rosário Cabrita et al. 2016) (Riesener et al. 2019)

Lean and Green	Kaizen, Pollution prevention, Waste management Employees and supplier Involvement Cross-functional team Inventory management, local sourcing	TPM VSM 5S SMED Kanban cellular manufacturing Poka-Yoke	- Improve Supply chain. - Improve Social Human Skills (Health, safety, Moral, Stress, Team sprit). - Reduce Environmental impact. - Improve the efficiency of system and equipment. - Improve the product durability. - Improve Human performance tasks. - Optimize the choice of material. - Minimize waste. - Optimize End-of-life and life cycle. - Reduce the emissions.	Innovation Longevity Reusability Re-manufacturability Dis-assembility Safety Cost Quality Sustainability TRIZ	(Udokporo, Anosike, and Lim 2020) (Farias et al. 2019) (Kaswan and Rathi 2020) (Farias et al. 2019) (X. Sun et al. 2018) (Bhattacharya, Nand, and Castka 2019) (Henao, Sarache, and Gómez 2019)
Lean 4.0	Industry 4.0 Interoperability Virtualization Decentralization Real Time Capability Service Orientation Modularity LEAN Kaizen Jidoka JIT Etc…	Robots Internet of things Simulation Cyber security System integration Cloud computing 3D Big Data Augmented Reality	- Enhance the human skills to use the new technologies of I4.0. - Enhance the performance of system by adding the new technologies of I4.0. - Allow Human to work with robots in collaborative way. - Improve Human performance tasks. - Simulate and follow in 3D products and production process. - Provide the communications between agents. - Make decisions autonomous and in real time. - Excite opportunities for solving complex problems. - Adapt quickly to a changing demand.	Smart tools 4.0 Human skills 4.0 Reconfigurability Agility Diagnosis Safety Supplier and customer integration Automation Autonomous	(Kolberg and Zühlke 2015b) (Yamazaki et al. 2016) (Bibby and Dehe 2018) (Slim, Rémy, and Amadou 2018)

2.7. Conclusion of this chapter

In this chapter, the review outlines the Lean in engineering design in the context of Industry 4.0. We aim to show how Lean thinking can be useful for integrating the maximum number of criteria required to optimize the six adopted components of production systems to enhance its performance from the early design phase under an Industry 4.0 vision.

Many works look similar, aiming for integrating Lean thinking from the early design phase, but their goals differ.

We see that many Lean functionalities can be considered from the design phase, either by classical design methods such as Design for X or by Lean Design. However, most of these methods do not provide for designers a systematic approach, covering in detail all of the performance criteria and Lean functionalities.

For our approach in the next chapter, we use the production system components, adopted by Benama (2016), which adds to the classical components, the energy system, and the buildings and structure.

Chapter 3. Lean-System-Design framework

3.1. Introduction

Due to the current innovative situation, to face industrial competitiveness, to satisfy the requirements of new technologies and the need of customers and users, performant systems must be designed in such a way to give more autonomy to users and machines. That will guarantee usability and safety of usage by the user and increase productivity by enhancing machine performance and reducing wastes and sources of errors and breakdowns.

As we know, production systems, with their components: Machines and equipment, humans (operators and technical), and computers and software, tend to increase productivity by adding new equipment and searching for new solutions. Firstly, the cost of improvements in existing systems could be the subject of further research and discussions. Secondly, new technologies can contribute to the development of new skills and the opening up of new horizons on waste elimination. Lean dedicates particular attention to improve production systems performance to enhance productivity by using some tools such as SMED, 5S, TPM, etc. Most of these tools require time, organization, user intervention, and budget. Considering Lean from the design phase might be a more appropriate solution, which guarantees more productive systems by optimizing the time of operation from the design phase. This leads to minor improvements via Lean in the use phase.

Our framework aims to improve industrial performance such as sustainability, agility, usability, flexibility, time-saving, cost-effectiveness, and safety, etc. by providing an approach to help designers in their design works to design a performant system in the context of Industry 4.0.

In this context, many questions may be raised:

- ✓ How Designer take into account the Lean requirements?
- ✓ How Designer take into account the information and conditions of use?
- ✓ Are there convergences or contradictions between the Lean requirements and Industry 4.0 requirements?
- ✓ Which functionalities of Lean could be considered from the early design phase?
- ✓ How can we help designers to choose solutions that do not breakdown the

system?

- ✓ How to solve the contradictions, if they exist, due to the integration of Lean from the design phases?

To answer these questions, we propose the following steps of our study:

(1) In section 1, we present a survey to understand how industrial companies take into account the condition of use from the early design phase.

(2) In section 2, we present our analysis of the convergences and contradictions of the implementation of Lean concepts and Industry 4.0 in production systems.

(3) In section 3, we provide our systematic approach: "Lean-System-Design", for integrating Lean functionalities from the design phases.

3.2. Analysis of industrial expectations for the integration of user tasks from the early design phase

To understand how industrial designers take into account the information and conditions of use from the early design phase, we surveyed more than 50 companies. We analyzed their design work and evaluated if they need a new structured method to provide a real image to understand what is going in the companies, what they do, use, and how they answer this problem.

Our proposed method aims to integrate the human factors and ergonomics from the early design phase (HFE), developed by (Xiaoguang Sun et al. 2018), and represented in the survey. But still, to consider all the other performance criteria related to the production systems and machines, and the user's skills towards a system, which needs improvements via Lean.

The survey has been answered by more than 50 experts in the world of design, which represented companies in France, Germany, and internationally in different sectors of activity such as machinery and equipment, industrial materials, automotive equipment, and products.

We have chosen these sectors of activity for the survey because Lean concerns the conditions of use and the mechanical part of the system. Moreover, we find quite a few cases of interactions between humans and machines in these industrial sectors.

The following is a list of the 17 survey questions:

(1) In your design work, are there any modifications (iterations)?

(2) In which stage (s), do design changes often occur?

(3) Choose the reason (s) for your design modifications.

(4) Are you currently integrating Human factors (HF) and use information into the design phase?

(5) In which phase (s) do you integrate the use information?

(6) Currently, how do you integrate the use information?

(7) What solution(s) do you choose when design modifications are needed?

(8) What are the consequences of introducing safety systems and additional procedures?

(9) Do you think that are you a "good" user of your product?

(10) Normally, when the product manual should be written?

(11) Usually, who should write the product manual?

(12) Are you interested in a method that allows you to eliminate or reduce the needs of safety systems?

(13) Would you like to introduce this method proposed by Sun and al.2018 to carry out design work?

(14) Do you want to systematically collect use requirements and information?

(15) Would you like to complete functional analysis with a task analysis?

(16) Would you be ready to define the input, output, control, duration, and support resources for each task required to perform a function?

(17) Would you ready to cooperate with us to test the method proposed by Sun and al.2018?

Based on a statistical analysis of the answers, we conclude that modifications often occur at all phases of the design process for different reasons. Among the reasons, respecting ergonomic standards and laws and meeting customer requirements are the most common.

Late integration of information of use and late development of the user manual can also cause these modifications. To solve this problem, designers implement some safety systems, which can decrease reliability. And sometimes, designers choose to design a new system, which can be very expensive.

We conclude that there are no systematic methods in the design work for integrating the HFE and the condition of use. Hence the importance of such research.

We have shown that most experts in the field of design in different manufacturing areas are interested in such a method that, from the early design phase:

- Integrate the information of use into the design phase.
- Optimize the human-machine interaction.
- Reduce the need to apply Lean and other methods of improving performance in the use phase.
- Integrate Lean principles from the early design phase to enhance the industrial performance.
- Respect the environment.
- Understand the operator (Behaviours, tasks, etc.) in his workplace to help him perform his tasks optimally in an Industry 4.0 context.
- Show concretely that the designer needs a useful tool to carry out optimally his design work.

Until now, 22 companies want to work with us. One company has already collaborated with us.

Our future work seeks to propose a new framework able to cover more criteria to make the system performant, agile, sustainable, etc.

Integrating Lean from the design phase can be useful to consider more criteria to improve the overall performance of the production system in an Industry 4.0 context. This leads us in the following to analyze the convergence and divergence between these two concepts to integrate them from the design phases.

3.3. Convergence/contradiction between Lean and Industry 4.0

From literature analysis, as we have seen earlier in the previous chapter, we noted that Lean and Industry 4.0 could combine to design an optimal and modern production system.

The concept of Industry 4.0 covers all phases of the system life cycle to design more efficient production systems, which seeks to make performant not only the use of systems but also their logistics, and maintenance, etc.

To more understand the convergence according to concrete examples mentioned in the literature. Table 3.1 gives some examples of the combinations of some Lean tools and principles and some Industry 4.0 technologies to improve and make the machine, human, product, and the management part more performant.

Table 3.1 Linking Lean to Industry 4.0

LEAN / I4.0	Poka-yoke	Andon	Heijunka	Man-Machine	Pull flow	SMED	VSM	5S	Standardisation	TPM	Visual Management	Kaizen
Smart Product		1	1		1		1					1
Smart Planner				1	1		1		1	1		1
Smart Machine	1					1		1		1		
Smart Operator	1	1	1	1		1	1	1			1	1

Table 3.2 illustrates our analysis of the implementation of industry 4.0 and Lean concepts, pointing out the convergences and contradictions.

The two concepts, Lean and Industry 4.0, share the same goal of considering the performance criteria to improve the system used or to be designed. For that, we are compared both according to performance criteria.

These analyses are carried out following the examples mentioned in the literature explicitly in Chapter 2.

The code "+" presents the effect of the implementation of Lean and Industry 4.0 on production systems according to criteria that influence the aspect of the production system and their ability to respond to market requirements and the integration of recent technologies.

"+" shows that there can be a low positive effect.

"++" shows that there can be a high effect.

"+++" shows that there can be the highest effect.

Some criteria are related to humans. Others are technical, depending on the machines or the process.

For this reason, for example, we have chosen to compose the criterion of autonomy in two aspects, one linked to the operator and the other for the machine. We have chosen to put "System Autonomy" as a divergence because it can affect human tasks. And for "Operator Autonomy", we have chosen to put in convergence because Industry 4.0 technologies can be a source of help for Lean application.

Table 3.2 Linking Lean to Industry 4.0 following some performance criteria

Criterion	I4.0	Lean	Convergence	Contradiction
Productivity	+++	++	The digital connectivity enables an automated and self-optimized production	
Flexibility	+++	++	Both increase the flexibility of production system	
Agility	+++	++	I4.0 makes the plant more agile	
Reconfigurability	+++	+		Lean does not propose more configuration
Extensibility	+++	++	Smart factory is self-adaptable	
Complexity	+++	+		I4.0 increases the complexity and Lean simplifies it
Automation	+++	+		Risk of a lot of automation and a reduction of the role of the man
System Autonomous	+++	+		I4.0 can make decisions autonomously via the RFID technology
Machine to Machine Interaction	+++	+		I4.0 interconnects machine without human interaction
Standardization	+++	+++	Is fundamental to guarantee interoperability	
Maintainability	+++	+++	can react in an autonomous way to resolve problem	
Diagnosis	++	++	Both promote the elimination of defect	
Elimination of waste	++	+++	I4.0 does not propose a structured method	
Team Work collaboration	+++	+++	Both require connecting operators with each other	
Decision Making	+++	++	Cloud availability makes decision making easier	

Human-Machine Interaction	+++	+++	New robots work side by side with humans to help him to do complex tasks	
Usability of Tasks	+	+++		Lean requires simpler task. Artificial intelligence may eliminate human tasks and reduce its role in monitoring operations.
Operator autonomous	+++	++	(AR) devices put all information that they need in the hands of operators in real time	

According to this analysis, Industry 4.0 is not in contradiction with Lean principles relating to customer satisfaction, reducing costs, and eliminating waste. But the risk which we think could be quite real nowadays engendered is the full automation that can limit the role of humans and almost can eliminate it, which is one of the crucial elements of the Lean philosophy.

Besides, considering the Industry 4.0 requirements from the design phase enables the development of flexible production systems, which can produce a variety of products without requiring major changes, more agile to adapt quickly to changing demand, reconfigurable to adapt quickly to new products. The integration of Lean from the design phases can concern all types of machines and industrial systems.

3.4. Lean-System-Design study

As we explained above, our objective is to help the designer to design a machine or system that did not need to apply Lean methods and tools to improve their performance in the use phase.

For this purpose, we have analyzed Lean functionalities and the requirements of Industry 4.0.

We noted that:

- Some Lean technical functionalities are general. Designers have already taken them on the specifications phase design, as criteria such as budget, standards, technical specifications, etc.

- Other non-technical functionalities, which depend on human tasks such as safety of use, and ergonomic, are mostly taken into account from the three other phases of design (Conceptual phase, Embodiment phase, and Detailed phase).

And then, we have identified the steps of our study:

(1) Identify the criteria that depend on Lean and I4.0.

(2) Classify the Lean functionalities according to the literature and the opinions of experts into:

a. Functionalities can be considered from the design phases. These functionalities can be classified into two categories:

- Functionalities are already considered from the design phases.
- Functionalities can be considered from the design phase based on our judgment and knowledge.

b. Functionalities that we do not think that can be considered from the design phase. For those functionalities, we justify the reasons why they could not be considered.

(3) Propose a list of criteria that could help designers not miss any functionalities (technical one and those resulting for lean).

(4) Then in the next step, to help designers to verify if they have considered all functionalities, we have proposed an evaluation checklist based on all criteria defined in the requirements phase (specifications phase). These evaluation criteria, depending on Lean functionalities, can be grouped as qualitative or quantitative types. Here, the selection of criteria relies on the designer's choice depending upon his focus like budget, quality, technical requirement, etc. So, he can give a priority weightage for each criterion.

(5) In this step, if the solution set becomes zero due to the integration of technical and Lean functionalities from the design phase, we propose to use the Inventive Design Method (IDM) (Cavallucci et al.2012). So, to find an innovative solution we combine our method with IDM. However, if in spite of this method, the designer does not find any solution based on all chosen criteria, we think that he has to drop some Lean functionalities and keep repeating these steps unless and until finds a set of solution concepts.

Figure 3.1 shows that Lean functionalities can be taken into account at each phase of the design process by following the procedures mentioned in the steps above.

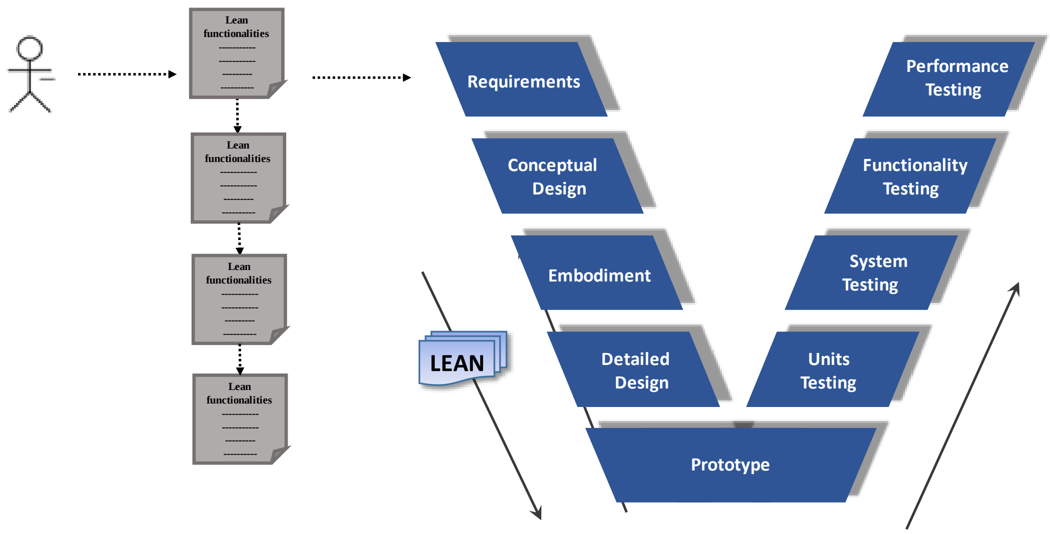

Figure 3.1 V-Modell of our study

3.4.1 Identified performance criteria

Normally, designers follow the imposed criteria to take into account the requested requirements.

According to Koren et al. (2011), the production systems require several characteristics and criteria such as automation, mobility, modularity, integration, extensibility, convertibility, and diagnostic ability to be reconfigurable.

Drohomeretski et al. (2014) consider the criteria quality, reliability, flexibility, speed, cost, and innovation as competitive priorities that lead to the best performance of manufacturing companies in southern Brazil. Based on the criteria: time, cost, quality, reconfigurability, and mobility, Benama (2016) proposes a methodology to design a mobile and reconfigurable production system. Ramos et al. (2020) use automation, processing, flexibility, usability, support assistance, and the cost of user training as evaluation criteria. Design for sustainability is crucial to enhance the social conditions, reduce the waste of energy and water, and improve the environmental conditions (Banerjee and Punekar 2020).

The list below in Table 3.3 presents the most widely used and known characteristics and criteria removed from literature according to the evolution of production systems paradigms (Riesener, Rebentisch, Doelle, Kuhn, & Brockmann, 2019), (Ren 2018), (Bibby and Dehe 2018), (Buer, Strandhagen, and Chan 2018), (Luthra et al. 2020), (Oleghe and Salonitis 2015), (Moro, Cauchick-Miguel, and Campos 2019) (Ciccullo et al. 2018).

Table 3.3 List of performance criteria

	Criteria	*Description*
1	Accessibility	Is the ability of system to be access easily.
2	Aesthetic	Is the ability to create products to catch customer eyes.
3	Availability	Is the ability of being good in a position to fulfil a required function under specified conditions, at a given time.
4	Agility	Is the ability to react quickly and flexible to unexpected changes in a dynamic environment.
5	Automation	Is the ability of the system to change the degree of automation of operations, depending on certain factors such as the production rate.
6	Autonomous	Is the ability of the use of robots for automating activities in a way that systems work autonomously and consciously aware of the surroundings that make them work collaboratively with the human.
7	Communication	Is the ability of system to exchange the information with interoperability through the networked machines at the shop floor and human (Machine-Machine (M2M) and Human to Machine (H2M)).
8	Complexity	Is the degree of complexity of system.
9	Convertibility	Is the ability to easily transform system functionalities to meet new production requirements.
10	Cost	Is the total cost of the system design.
11	Customization	Is the ability to make a personalized flexibility that cover the DMS and FMS.
12	Diagnosis	Is the ability of the system to analyze current situation to quickly diagnose the sources of failures and quickly correct operational defects.
13	Extensibility	Is the ability of system to modify easily the capacity of production by adding or removing resources (e.g. machines) or by replacing system components.

14	Flexibility	Is the ability to adapt operations whenever necessary and respond quickly, whether it is due to changes in demand or needs of the production process;
15	Human skills 4.0	Is the capacity of users to have the skills to work in the context of Industry 4.0.
16	Innovation	Is the ability to design new products that are more diverse development times than competitors.
17	Integration	Is the ability of the integration of the systems in different sites allowing a more adequate control of the production indicators of the plant.
18	Leadership	Is the ability of the cooperation of employees and leaders in their mutual striving for perfection.
19	Multi-skill work	Is the ability of user to perform several tasks.
20	Mobility	Is the ability to the ease movement of certain equipment within the production system in order to facilitate its reorganization.
21	Modularity	Is the ability to use modular components to facilitate their reconfiguration, maintenance, or replacement.
22	Maintainability	Is the ability of equipment to be easy to repair and maintain.
23	Processing	Is the velocity in exchange for information and commands given by the user.
24	Productivity	Is the efficiency and the production speed.
25	Quality	Is the ability to offer products that meet or exceed project specifications;
26	Reliability	Is the probability that an item will perform a required function without failure under stated conditions for a stated period to meet delivery deadlines.
27	Safety and ergonomics	Is the ability to adapt works, tools, and the workplace to the user to ensure the human-machine interaction, and to respect safety laws and standards.
28	Standardization	Is the following of the global standards like the International Organization for Standardization (ISO).

29	Self-Cleanliness	Is the ability of the system to stay clean, tidy, and standard.
30	Smart technology 4.0	Is the ability to integrate new technologies of Industry 4.0.
31	Sustainability	Is the ability to cover economic sustainability (the production or manufacturing costs at plant level), environmental sustainability, and social sustainability (waste reduction, emissions mitigation, lowering energy consumption, improving resource utilization efficiency, and decreasing the frequency of environmental accidents).
32	Support Assistance	Is the ability of the system to solve specific problems of the system.
33	Supplier and customer integration	Is the ability of the system to provide a platform to exchange in real-time all information related to productivity and delivery.
34	Team work	Is the ability of team work.
35	Usability	Is the ability of the system to be used easily.
36	User satisfaction	Is the percentage of customer and user satisfaction based on actual cases and previous experiences.
37	Longevity	Is the ability to increase the life of product along with easy reparability, upgradability, and recyclability.
38	Reusability	Is the ability to make minor changes for the same purpose by keeping the original design.
39	Remanufacturability	Is the ability to reprocess used products to recovery the original structure or to make new patterns keeping the same functionality.
40	Disassembility	Is the ability to disassemble, sort, and clean materials for recyclability.

3.4.2 Lean-System-Design approach

Our goal is to design a system 4.0 (Production system, machines), agile and sustainable, which respects the requirements imposed by customers, users, and the environment, and adapt quickly to the customization of products in real-time. It is done by implementing the Industry 4.0 technologies and optimizing the three dimensions of sustainability, economic, social, and environmental.

Our system 4.0 depends on several actors that react to each other.

The Octopus diagram, as shown in Figure 3.2 and Figure 3.3 below, highlights the relationships between the different elements and factors of the system.

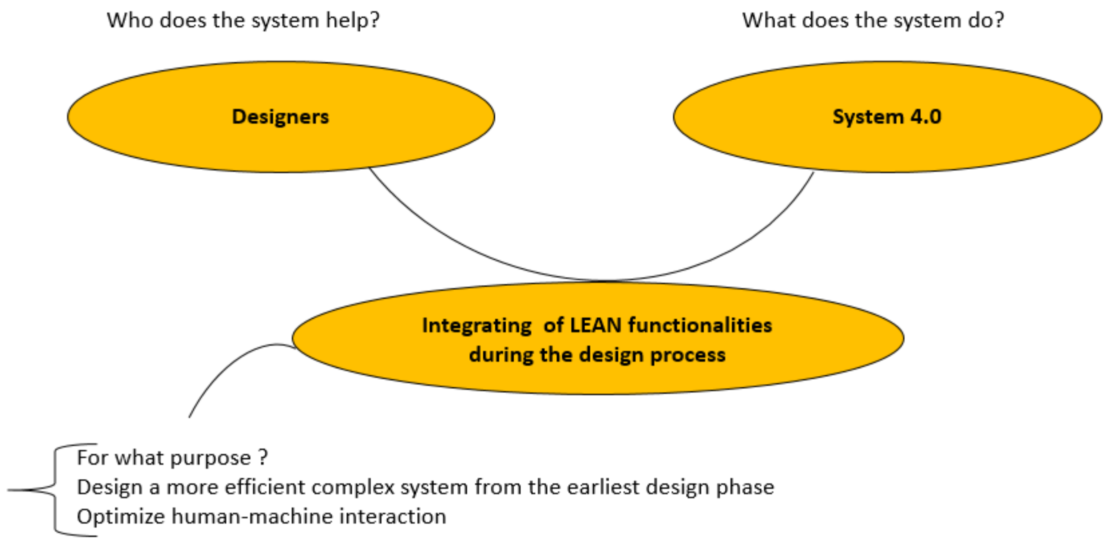

Figure 3.2 Identification of needs (functional and Lean functionalities)

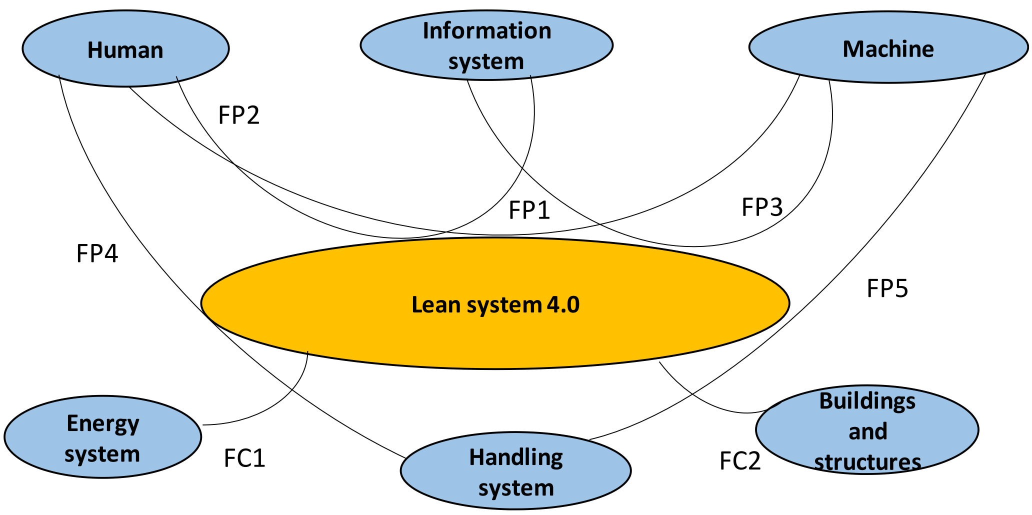

Figure 3.3 Octopus of Lean-System-Design system

The system functions are classified into two categories that each one can contain some Lean functionalities:

- Primary Function (FP)
- Constrained Function (FC)

FP1 Allow Human to use machine.

FP2 Allow humans to have the necessary information.

FP3 Allow machines to have the necessary information.

FP4 Allow humans to know transfer functions.

FP5 Allow machines to know the transfer functions.

FC1 Take into account the ecological aspect.

FC2 Respect buildings and structure.

The purpose is that Lean should cover all the functions of the Octopus diagram.

Thus, we propose to the designer the following approach presented in Figure 3.5, and composed of the following steps:

1. In step 1, as a classical design method, the designer defines all specifications demanded by the client.

As we know, an engineering system design is represented as an input-output transformation, as shown in Figure 3.4.

Input concerns all the product specifications and requirements that the designer need to design a performant final system.

The output regards the prototype that can be tested by designers and users.

The designer aims to design a system that can meet the needs of the final user and customers. Depending upon the situation, the criteria are to be selected.

Nowadays, the new smart systems require some performance criteria, such as agility to maintain competitiveness, sustainability to improve the three economic, social, and environmental dimensions, digitalization to meet the Industry 4.0 requirements.

The collected criteria presented in the previous section constitute the Input requirements derived from marketing, user and customer experiences, environmental laws, etc.

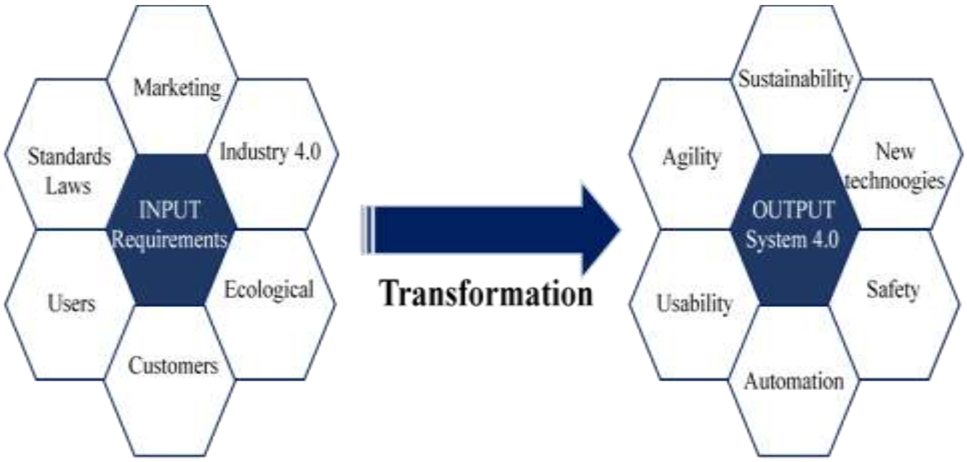

Figure 3.4 From Requirement to Final system

2. In step 2, the designer provides a functional analysis to define technical functions, service functions, and constraints.

3. In step 3, the designer elaborates a list of criteria regarding the objectives and the constraints.

4. In step 4, the designer adds Lean functionalities, which allow fulfilling the chosen criteria in step 3, to the functionalities required by customers (technical functionalities).

5. In step 5, the designer does his work to develop a solution to fulfill all required functionalities (technical functionalities and lean functionalities). However, we did not impose here how a designer should do. This step could be different in the function of his field and artifact subject of the design process. Depending upon the situation and condition, the designer can use adequate available methods and tools in his possession (FAST, SADT, etc.) or his expertise.

An optimal solution is one that meets all the criteria defined by the designer. We look for an optimal solution from the very first time and without iterations that satisfies all the criteria chosen by the designer.

6. In step 6, if the designer did not find any solution after integrating all functionalities and constraints that he wants, that means: "The solution zone becomes zero".

So, to solve the problem and to find innovative solutions, we propose to use the Innovative Design Method, which is an extension of TRIZ for the generation of solution concepts by solving contradictions. If in spite the use of IDM, the designer cannot find a solution, he has to relax some constraints by taking off some Lean functionalities or other constraints (cost, etc.).

The more criteria to be integrated, the more contradictions would arise, and therefore more details would need to be provided to the designer. Theoretically, this is possible, but it is up to the designers to see which criteria to take into account at a given time "t" according to their field and objectives.

7. In Step 7, the designer follows the Lean Evaluation Check-list before prototyping to avoid any missing.

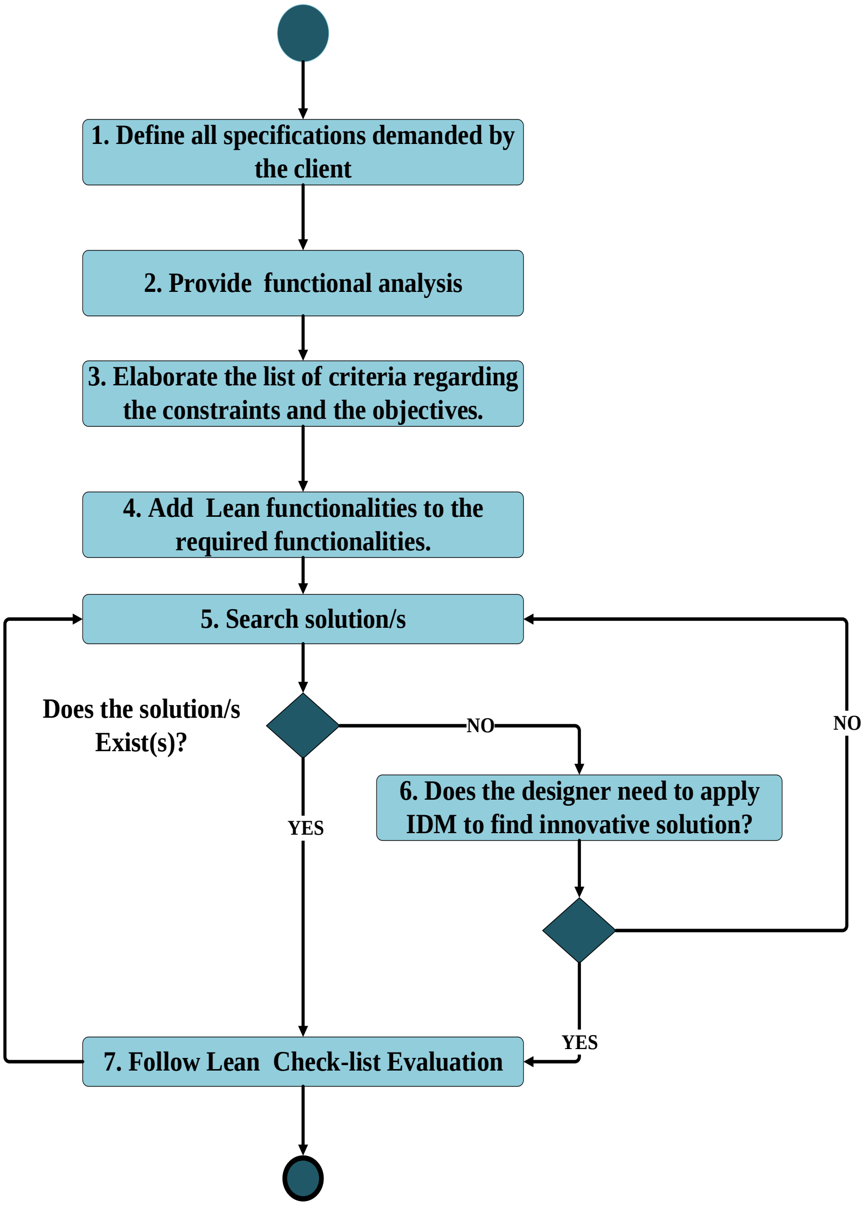

Figure 3.5 Lean-System-Design steps

To apply this proposed method, in Figure 3.6, we adopted the production system design method developed by Pahl (Pahl et al. 2007), which has four phases:

1. Initialization phase: In this phase, the design problem is defined; data from Lean and Industry 4.0 can be provided.

The functional specifications document (FSD) will be constantly improved and refined according to Lean requirements and functionalities.

The functional specifications contain all specifications and information that the system must perform to satisfy all requirements.

2. Conceptual Design: This data conceives the initial functional specifications. From the specifications, the concept of the main solution is chosen to be developed.

3. Embodiment phase: When the requirements are obtained, the function hierarchy can be developed, using Functional Analysis (AF), with the constraints of the configuration of functions and the linkage between the sub-functions.

4. Detailed phase: Finally, in the detailed design, the design is based on a complete technical description of the complex system.

After the detailed design, we provide a check-list evaluation of Lean functionalities integration.

Depending on the results, the designer could rethink other solutions more Lean and thus guarantees more performance to the final optimal solutions envisaged.

And therefore, a new attempt to resolve contradictions and to find innovative solutions can be implemented by using IDM.

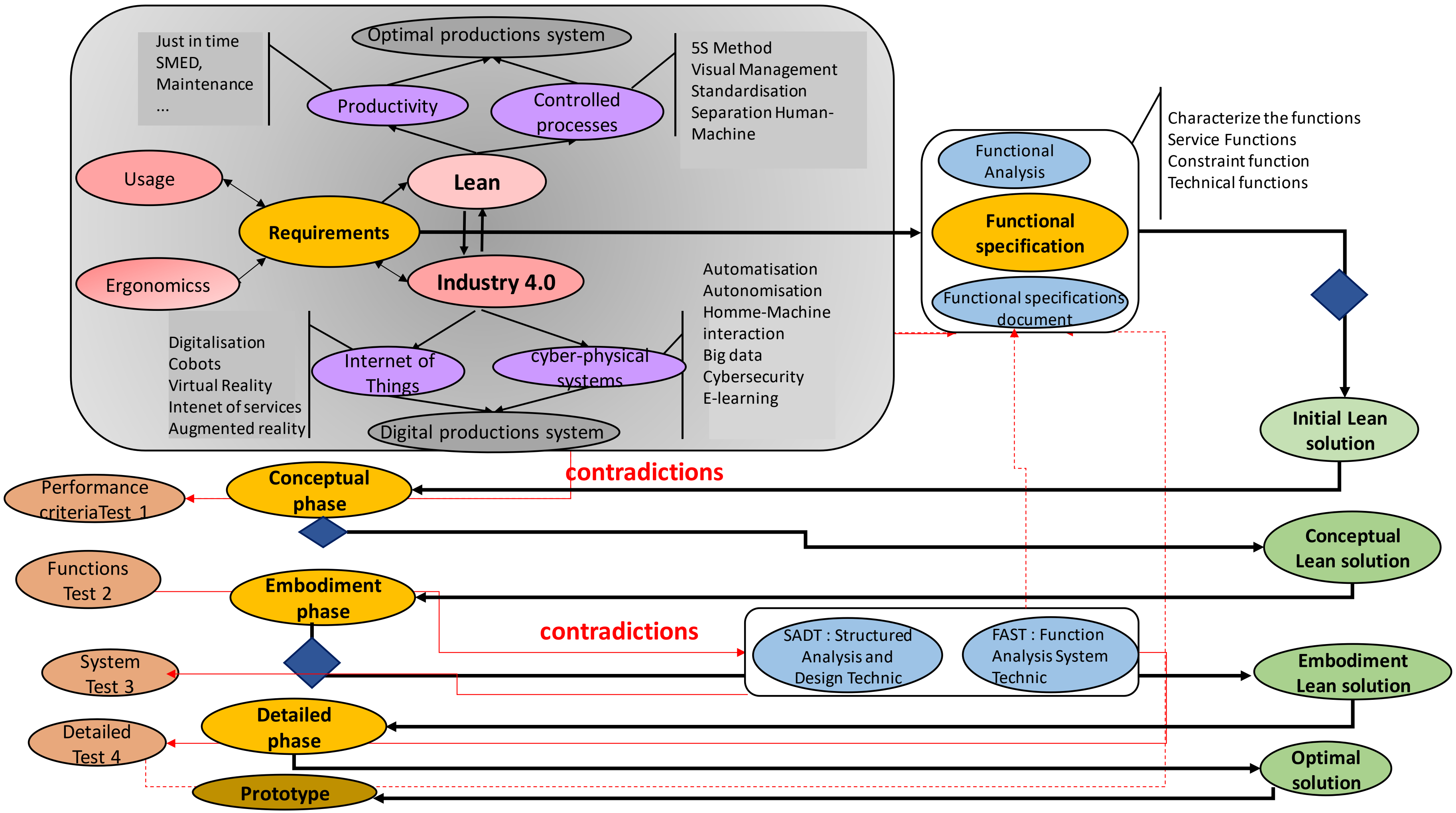

Figure 3.6 Lean-System-Design framework

3.4.3 Lean functionalities classifications

In the previous chapter, we have identified the Lean functionalities. However, there is a question: Are all these functionalities already integrated, or could they be integrated from the design phases?

We summarize Lean functionalities to optimize the octopus diagram functions, according to the literature and the opinion of some Lean experts. For that in Table 3.4, we classified these functionalities into two categories:

(1) Functionalities can be integrated from the design phases. These functionalities are coded (1).

(2) Functionalities cannot be integrated from the design phase. These functionalities are coded (0).

"0" shows that they cannot be integrated because of the need for data, which is not available (for example, lead time data is related to production system organization).

"1" shows the functionalities which:

1) Are already integrated into other methods. For example, functionalities of the “5S Method”, which improves the criterion of safety, are already treated by the method of "Design for safety" (R. Houssin et al. 2006). And, the functionality of “Reduce breakdowns time” is already treated by (Coulibaly, Houssin, and Mutel 2008).
2) Could be integrated from the design phases in our opinion, and for whom we did not find references in literature.

For each Lean functionality, we give the principal function identified in the Octopus diagram. These comments concern more the production systems. But it can also be generalized to all types of systems and machines.

Table 3.4 Lean Functionalities following Octopus diagram and the integration from the design phases

Lean functionalities	Related functions	Integrality	Method of Design	References
- **Base your management decisions on a long-term philosophy**.	ALL	1	Toyota design rules	(Krijnen 2007) (Jt Black, 2007)
- **Create a continuous flow process**.	FP3 FP5	1	Industry 4.0 Simulation	(Tiacci 2017)
- **Minimize adjustments.** - **Reduce the six big losses (breakdowns, setup and adjustment time, idling and minor stoppages, and reduced speed).**	FP1 FP2 FP2 FP3 FP4 FP5	1	Flexible manufacturing cells Design by simulation Lean – TRIZ Axiomatic Design Toyota production system design Design for maintainability QFD Design for quality Design for reliability	(Deshkar et al. 2018) (Hitomi et al. 1989)
- **Reduce quality losses (defects in the process and reduced yield)**.	FP3 FP5	1	Design for maintainability QFD Design for quality	(Neumann et al. 2016) (Coulibaly et al. 2008)
- **Improve Human performance tasks**.	FP1 FP2 FP4	1	Design for quality Design for safety Design for use	(Sun et al. 2019) (Sun et al. 2018)
- **Improve manufacturing equipment efficiency by improving the overall manufacturing performance.**	FP3 FP5	1	Lean design Design for maintainability TPM-TRIZ	(Antosz et al. 2019) (Atilano et al. 2019) (Houssin et al. 2014)

- **Improve safety and workspace**.	ALL	1	Design for safety Human center design	(Vilda et al. 2019) (Sun et al. 2018) (Houssin et al. 2006)
- **Produce what the costumers order only.**	ALL	1	Design for agility Industry 4.0 principles and tools	(Lu et al. 2011) (Kesen et al. 2020) (Ezema et al. 2017) (Sivakumar et al. 2009)
- **Produce in just in time**.	FP1, FP2, FP3, FP4, FP5	0	Smart Assembly systems Real time 4.0 Computer Aided Synthesis Work space design, I4.0 Cellular manufacturing	
- **Apply a communication between the agents (supplier, process, client)**.	FP2	1	Product-Service systems (PSS) Value Stream Map	(Jiménez et al. 2016)
- **Smooth production by volume and product mix.**	FP3 FP5	1	simulation analysis Design for reconfigurability Design for agility	(Kesen et al. 2020) (Weizhuo Lu, et al. 2011)
- **Remove the waste of Mura or unevenness and Muri Irregularity**.	FP1, FP4	1	Design for safety Work station design Simulation Industry 4.0 tools	(El Mouayni et al. 2020) (R. Houssin et al. 2006)
- **Produce in small-lot**.	FP3 FP5	1	Design for six sigma Simulation Toyota production system design	(Jugulum et al. 2008)
- **Make problem visible.** - **Stop system when there is an abnormality or problems.** - **Alert operators in case of problems.** - **Find the root cause of problems.**	FP1 FP2 FP3 FP4 FP5	1	Design for safety Design for additive manufacturing Lean design for X Human centric design Industry 4.0	(Pradel et al. 2018b) (Stadnicka et al. 2019) (Gazzaneo et al. 2020) (Uwe Dombrowski, et al. 2018)

- **Avoid Human errors**.	FP1, FP2, FP3, FP4, FP5	1	Design for safety Design for human safety Work station design Simulation Industry 4.0 tools Design for use	(Malik et al. 2019) (El Mouayni et al. 2020) (Sadeghi et al. 2016) (Xiaoguang Sun et al. 2018) (H. Sun et al. 2013) (Xiaoguang Sun et al. 2019) (R. Houssin et al. 2006)
- **Increase the quality.** - **Improve the final product.**		1	Design for quality Design by user experience Lean Product development Lean Design Through Computer Aided Synthesis	(Järvenpää et al. 2019) (Becker et al. 2015) (C. H. Ko 2017)
- **Maintain the regular output of the process.**	ALL	1	Design for Standard and Laws Industry 4.0 principles and tools	(Weyer et al. 2015)
- **Maintain the regular timing.**	All	0		
- **Clarify waste.** - **Detect the anomaly.** - **Implement an immediate solution.** - **Make indicators visible.** - **Improve information visibility.**	ALL	1	Design for six sigma Design for manufacturability Industry 4.0 integration Lean design for X Design for Additive manufacturing	(Baptista et al. 2018) (Atilano et al. 2019)
- **Use technology to support people.** - **Encourage people to consider new technologies**.	ALL	1	Design for reliability Automation	(D. Das et al. 2009; He et al. 2020; Gargama, Chaturvedi et al. 2014)
- **Grow Leader from the system.** - **Teach employees.**	FP1 FP2 FP4	0	Lean design for X Toyota production system	(Laureani et al. 2019) (Seidel et al. 2019)

- **Involve Human Skills.** - **Promote operators contribution.**	FP1 FP2 FP4	0	Industry 4.0 technologies Human centric design Training Simulation and virtual reality	(Gazzaneo et al. 2020) (Vilda et al. 2019)
- **Respect for your partners and suppliers**.	FP1 FP2 FP4	1	Product-Service systems (PSS) design Axiomatic Design approach QFD (Quality Function Deployment), TRIZ Design for X	(Kubota et al. 2017) (Girgenti et al. 2016) (Y. H. Wang et al. 2017)
- **Engineers go to observe processes.** - **Find solutions**.	FP1 FP2 FP4	0	Training Virtual reality Industry 4.O	(U. Dombrowski et al. 2019) (Brad, et al. 2016)
- **Consider all the options and agents of system**. **before making decision**.	FP1 FP2 FP4	1	Training Virtual reality Industry 4.O Artificial intelligence	(Hong et al. 2018)
- **Improve the Workspace**.	FP1, FP2,, FP4,	1	Workstation design Design for safety Ergonomics requirement Lean and Green	(Y. Koren et al. 2013) (Xiaoguang Sun et al. 2019) (H. Sun et al. 2013)
- **Improve the process continuously.** - **Improve the standard.** - **Improve Human skills**	All	1	Agile process Design for six sigma Collaborative design TPS design TRIZ User centered design	(Baschin et al. 2019) (Siltala, et al. 2019) (Hernandez-Matias et al. 2008) (Cochran et al. 2017) (Maia et al. 2015)
- **Eliminate waste of MUDA.**	FP1, FP2, FP3, FP4, FP5	1	Simulation VSM Lean Design Design for X Design for six sigma	(D. Mourtzis, Fotia, et al. 2017) (Pullan et al. 2013) (Yang et al. 2015) (Gonçalves et al. 2017)

- **Lead Time Reduction.**		0		
- **Enhance the variety of production.** - **Enhance the effectiveness response to the customer change needs.** - **Apply skills from different company functions from experts.**	ALL	1	Design for agility Design for customer satisfaction Design for reconfigurability	(Siltala et al. 2019) (Riesener et al. 2019) (Baschin et al. 2019)
- **Improve Supply chain.** - **Improve Social Human Skills.** - **Reduce Environmental impact.** - **Improve the efficiency of system and equipment.** - **Improve the product durability.** - **Improve Human performance tasks.** - **Optimize the choice of material.** - **Minimize waste.** - **Optimize End-of-life and life cycle.** - **Reduce the emissions.**	All	1	TRIZ Lean design for X Design for environment Design for sustainability Design for manufacturing Design for assembly/disassembly Supply chain design Lean Product development	(Guio et al. 2017) (Battaïa et al. 2018) (Melnyk et al. 2014) (González Chávez et al. 2019) (Kurdve et al. 2018) (Kurdve 2018) (de Souza et al. 2019) (Navas et al. 2015)
- **Enhance the human skills to use the new technologies of I4.0.** - **Enhance the performance of system by adding the new technologies of I4.0.** - **Allow Human to work with robots in collaborative way.** - **Improve Human performance tasks.** - **Simulate and follow in 3D products and production process.** - **Provide the communications between agents.** - **Make decisions autonomous and in real time.** - **excite opportunities for solving complex problems.** - **Adapt quickly to a changing demand.**	All	1	Industry 4.0 LEAN 4.0 Human centric design Collaborative Human-Robot Lean design for X Smart factory Cyber-physical system 3D printer Design for additive manufacturing Lean Product development Lean 6 sigma	(Graessler et al. 2019; Gazzaneo, et al. 2020; Waschull et al. 2020; Büchi, et al. 2020; Zolotová et al. 2020; Jones et al. 2018) (Cunha et al. 2003) (Hagemann et al. 2019) (Bettermann et al. 2019) (Elhoone et al. 2020) (Sony 2020)

According to these analyses, we conclude that some Lean functionalities cannot be considered from the design phases because of the need for data about manufactured pieces, consumer orders, or machines and company constraints (local, ranges), even though that there are studies that mention these cases.

For example, "Just in time" requires to know the delivery dates of parts and to order the first meters on time. "Maintain the regular time" is in link with product data, which could be unknown. "Produce in small-lot" is linked to the customer request, and it is a business rule for production management if the system is designed for a known product family.

Although, some studies evoke the possibility of taking into account certain functionalities related to production and customer demand. The machines are designed and placed in a way that they can respond to the variety of products. However, our opinion and the opinion of experts assert that certain criteria such as productivity and product quantities may vary from one customer to another. The design can of course help the system to react and adapt. But we preferred to put 0, because in our opinion, once the system is designed to respond to such a given for example, in some cases it will be locked on these data and require improvements. The "Reconfigurability", due to the technologies of smart factories, can respond to this problem.

3.4.4 Check-list of criteria

As we mentioned in Step 1 of the proposed approach, the designer has ranking criteria depending upon their importance.

While generating solution concepts, the criteria in the check-list will be ensured to fulfill by the generated solution concepts.

If the designer sees that he has taken into account the most important criteria for a chosen solution, he can, in this case, accept the solution according to their evaluation.

For example, he may even choose criteria for evaluating solutions.

The scale of grading is:

"1" Normal: this point is not compulsory to fulfill.

"2" Important: this criterion is better to fulfill, but it is not compulsory.

"3" High important: this criterion is must be fulfilled, and cannot be skipped.

For the concept solution, we have chosen here three evaluation criteria:

"Cost" refers to the projected budget for the solution selection.

"Time" refers to the expected time to carry out the chosen solution.

"Capability" refers to the technical and human capabilities to accomplish the solution.

And for the evaluation criteria, we give the scaling of "1", "2", and "3" with the same grading scale as mentioned previously.

Based on these evaluations, the choice of solution is the designer's choice.

In Table 3.5, the designer can find a solution in which the criteria for high degree of importance i.e, "3" are taken into account. Hence, he can validate this concept solutions “S0”.

In the case in which the criteria of important weight could not be taken into account, the designer can resort to Step 6 of the IDM methodology. This is the subject of the following section.

Table 3.5 Our study following the evolution of manufacturing paradigms

Criteria	**Degree of Importance**	**Lean functionalities**	**Solution concepts**	**Evaluation**			**Integration**
				Cost	**Time**	**Technical capabilities**	
X0	3	….	Sol 0	3	1	2	X0 Yes
X1	3						X1 Yes
X2	3						X2 Yes
X3	3						X3 Yes
X4	2						X4 Yes
X5	1						X5 No
X6	1						.
			Sol 1				
			Sol2				

3.4.5 Inventive Design Methodology to resolve contradictions

Sometimes the consideration of all the Lean functionalities corresponding to the criteria leads us to a zero solution. For that, we use the inventive design to solve contradictions and find solutions to innovative solutions.

The Inventive Design Methodology (IDM) is a systematic approach proposed by Cavallucci et al. (2012) to eliminate the limitation of classical TRIZ and to supplement its body of knowledge with other theories like graph theory. This methodology contains four phases. In the following, we briefly explain these phases:

(1) Phase 1: Initial Situation Analysis: In the first phase of IDM, the designer collects all the knowledge by reviewing the available data on the subject, and translates them

into a graphical model. This graphical model, which is called a problem graph, is a network of connected problems and partial solutions. In the following, to formulate the contradictions, the action parameters should be extracted from the problems and evaluation parameters from partial solutions (Zanni-Merk, Cavallucci, and Rousselot 2011).

(2) Phase 2: Contradiction formulation: In this step, the designer could apply the poly-contradiction template, to organize the extracted parameters in the last step, to formulate the contradictions. The contradictions are the barriers to the development of the system. These contradictions are essential to apply TRIZ techniques and methods in the next steps (Cavallucci 2014).

(3) Phase 3: Solutions Concepts Synthesis: After formulating the contradictions, the designer applies the tools and techniques, which has been proposed by TRIZ to resolve the contradictions. The contradictions Matrix is one of these tools, which ordered 39 improving parameters and 39 worsening parameters on a vertical and horizontal axis to interact with one another. This matrix, in the interaction of the parameters, proposes the concepts, which could help to resolve the contradictions (P. R. N. Childs 2014).

(4) Phase 4: Solution Concept Selection: At the end of the process, the external experts should evaluate the impact of each concept on the graphical model in the first step of IDM. The applied tool for doing this evaluation, it is called Pugh's (Cavallucci, Rousselot, and Zanni-Merk 2011).

To find the contradictions, it is necessary to capture the expertise of the domain by questioning the experts or by extracting in canonical form the knowledge of the domain, on the use of algorithms that can be automatically or semi-automatically populate the ontology and then alleviate the work of the experts (Souili et al. 2015).

To show the usefulness of IDM on Lean functionalities integration, for example, we focus on integrating certain Lean functionalities right from the design phases, which have a positive effect on waste reduction (Mura and Muda) to reduce the expected downtime that could occur for the production machine without reducing the reliability and availability of the system.

Normally, Lean pays attention to reducing the production and configuration time by optimizing downtime (change over time, adjustments, preventive maintenance, outages, and micro-stops). For example, Single-minute exchange of Die (SMED) optimizes the changeover time. SMED offers a fast and efficient way to convert a manufacturing process into a product change. SMED uses a methodology, some techniques, and tools that have a positive impact on the flexibility of existing systems and machines.

Further, some other Lean tool as 5S, related to the workstation, users, and machines, improves quality management, maintains the workplace, the safety of users, optimum productivity, and minimum wastes and keeps standardized of the system.

The main functions of 5S are:

(1) Sort (Seiri):
- Keep things that are necessary.
- Remove unnecessary things.
- Time-saving.
- Eliminate obstacles.
- Increase safety.

(2) Set in Order (Seiton):
- Arrange items in close proximity.
- Make the system easy to use.
- Time-saving to access tools or items.

(3) Seiso (Shining):
- A clean and safe workplace.

(4) Standardise (Seiketsu):
- Standardized clean-up.
- Involve users.

(5) Sustain (Shitsuke):
- Sustain the disciplines.

So, we share the same goal of SMED and 5S on the conversion of the possible internal operations to external operation and the ensuring of the optimal conditions in terms of safety and waste reduction during the Human-Machine interaction.

During the design phases, we can differentiate four types of operations:

Technical operations: Operations that can perform by the machines without the intervention of the user.

And Socio-technical operations: Operations that can perform with the interaction between the user and the machine

Internal operations: Operations that can only perform when the machine is at a stop.

And External operations: operations that can be performed while the machine is running.

But we ask the questions early from the design process:

- What do they force the designer to choose internal operations?

- How could they do to convert technical solutions requiring internal operations to another one requiring an external one?
- How could improve the safety of the user without decreasing the productivity of the machine?
- Are there solutions to keep the machine more productive?
- Are there solutions to keep the machine and workplace clean?
- Are TRIZ could be useful to find innovative solutions?

To answer these questions, a function, which is defined as a conceptual model of a system, can break down into sub-functions of lower complexity. The overall function is a combination of individual sub-functions to identify sub-functions that facilitate the future search for solutions and combine these sub-functions into a simple function structure.

A function tree model represents the result of the specifications of functions, which aims to analyze the functions and find some contradictions, as shown in Figure 3.7. This inventive method is performed iteratively based on the decomposition of tasks, following these steps below:

(1) Analyze and elaborate system functions.

(2) Classify the operation of the function into internal and external.

(3) Convert internal operations into external operations by using IDM.

(4) Convert internal operations to external operations by using IDM.

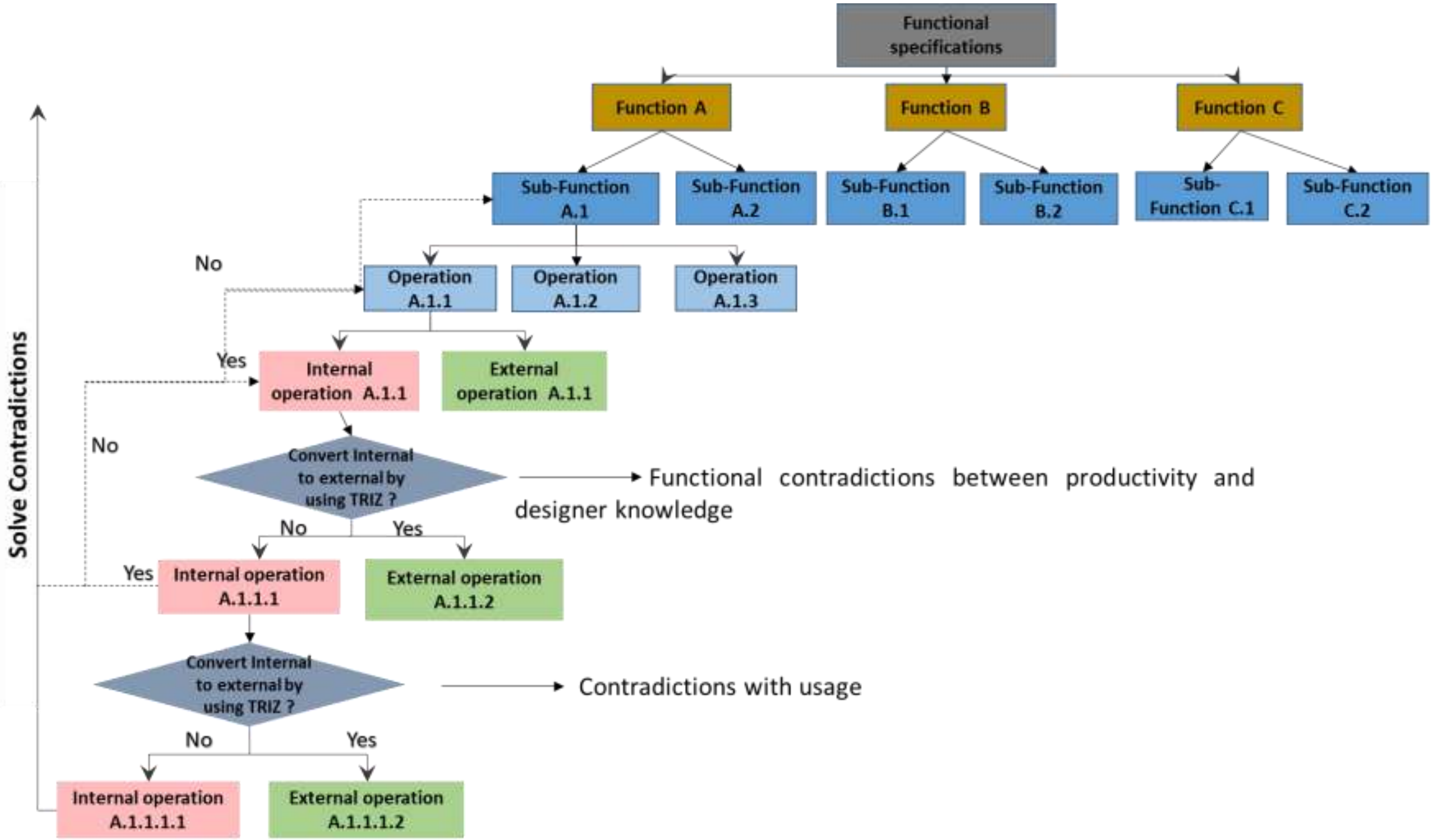

Figure 3.7 Resolving contradictions due to the conversion of internal operation in external one

3.5. Conclusion of this chapter

In this chapter, we proposed an approach to improve the performance of production systems by considering Lean functionalities from the early design phases in the context of Industry 4.0.

In this context, we explored the possibilities of proposing new methods and tools to help the designer to design a performant system without applying some Lean tools to improve the existing system.

As we have shown, many methods mentioned in the literature integrate disciplines, concepts, and criteria from the early stages of system design to meet the needs of customers and users and to reduce modifications by adding additional procedures to the production process and machines, which increase the industrial performance.

So, we have proposed a systematic approach for integrating Lean functionalities from the early design phase following the list of performance criteria to meet the objective to design a performant system from the early design phases.

For that, we firstly have identified and listed the required criteria for the performant system. Secondly, we have listed the functionalities of Lean and classified them according to their integrability or not in the design process. The designer has to consider all functionalities (technical and Lean) when researching the solution. If this leads the designer to a set of solutions equal to zero, we propose to use the inventive design method (IDM) to find some innovative solutions.

In the next chapter, we introduce three applications of the Lean-System-Design approach to illustrate the feasibility, the usefulness of IDM, and the possibility of applying it to a service system.

Chapter 4. Applications

4.1. Introduction

In this chapter, we present the feasibility of our framework in three case studies.

The first case shows the steps of the methodology for the design of a smart waste treatment machine.

The second case is pedagogical but significant for using the Inventive Design Methodology (IDM) in resolving contradictions due to the Lean functionalities integration.

The third case shows the opening to the design of service systems.

4.2. Case study 1: Smart waste treatment machine

In the context of sustainability and the implementation of Industry 4.0 technologies, the issue of waste recycling is increasingly addressed. As raised by several waste sorting centers, the transfer of recyclable waste to the treatment center (waste-disposal companies) generates high transport costs and considerable energy losses. For this reason, reducing the volume of waste before transport could reduce the costs and losses associated with its transport to the treatment center.

For this purpose, to solve these problems of high transport costs and recyclability, and energy losses of the waste of beverage dispensers, they decided in the mechanical department of INSA of Strasbourg to design an integrated and smart waste treatment systems, which would be placed next to the beverage dispensers. And thus, the user can throw his drink into the system, which has to recycle the bottles and cans.

The CAD-Calculation was carried out as part of a multi-disciplinary project by engineering students from the mechanic's department of INSA of Strasbourg on the design of industrial machines. The detailed technical parts are not shown for the reason of confidentiality.

During the design work, we have followed the steps of our Lean-System-Design approach, which is mentioned in chapter 3.

4.2.1 Application of Lean-System-Design

Step 1. Define all specifications demanded by the client

The purpose of this case is to design a system that would be placed next to the beverage dispensers so that the user could throw the empties cans of his drink into the system, which has to recycle bottles and cans from 33 to 50cl (most common sizes) (Figure 4.1).

Figure 4.1 A range of Products

This system would sort the cans and the bottles that people would throw away. Also, it would transform and reduce the volume of those wastes by grinding the plastic bottles and crushing the metal cans. Finally, the system must be easy to use by a large number of users.

<u>Step 2. Provide functional analysis</u>

Classical functional analysis was carried out to identify all technical functions and constraints regardless of Lean functionalities.

In Figure 4.2 we show the functions of the system:

- Primary Functions (FP)

FP1 Allow users to use the machine.

FP2 Allow machine to sort waste into three families: PET, LDPE, metal.

- Constrained Functions (FC)

FC1 Take into account the ecological aspect.

FC2 Respect standards and laws.

FC3 Allow the machine to have the necessary information about the system and the transport, and the waste-disposal companies.

FC4 Respect buildings and structure.

FC5 Ensure the safety of users.

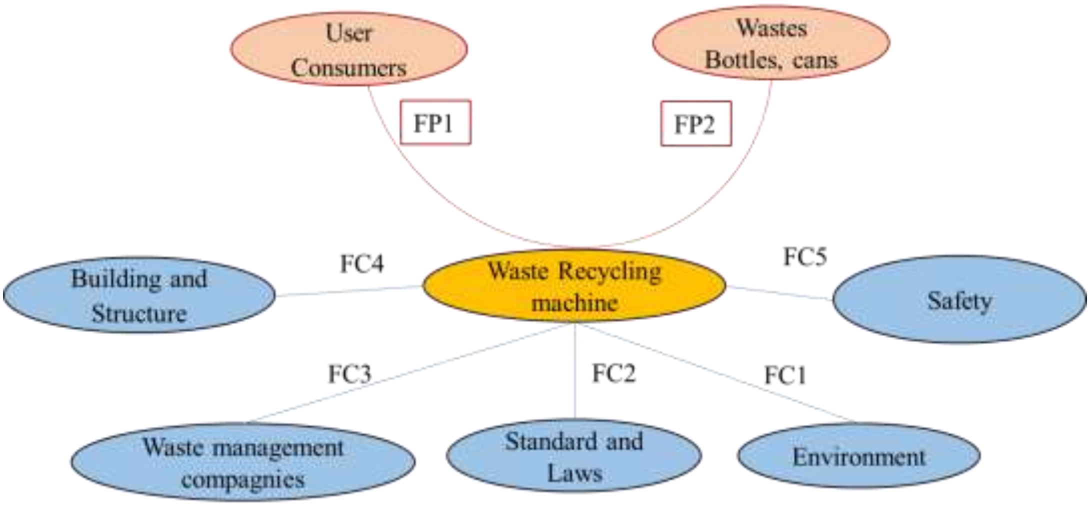

Figure 4.2 Octopus diagram

<u>Step 3. Elaborate the list of criteria regarding the constraints and the objectives</u>

The most required performance indexes are the criteria that guarantee:

Ecology (Sustainability): Allowing a recycling efficiency that is close to 100%, thanks to the separation system for aluminum, plastic ((PET (Polyethylene Terephthalate), LDPE (Low-density polyethylene), etc.).

Economy (Cost): Placing the machines in front of the beverage dispensers reduce transport and logistics costs. Besides, the separation of raw materials also reduces costs. For example, separated PET and LDPE plastics cost ten times more than mixed material.

Usability: Simplifying the system is significant for the sustainable aspect and the user satisfaction.

Recyclability: Allowing a low treatment rate, which is significant for longevity.

Smart technology (Industry 4.0): Scheduling the waste recycling by connecting the system to a central network, which enables the management of waste as raw material, or available for recycling. It includes the optimization of raw material collection and inventory management.

User satisfaction: The consumer of the drink participates directly in the protection of the ecosystem.

Human-machine communication: Due to its electronic interface and its location in front of the beverage dispenser, these machines must offer easy-to-use human-machine communication.

And there are some other criteria such: Safety, Automation, Agility, Availability, Diagnosis, Maintainability, Self-cleanliness and, Human skills 4.0.

Step 4. Add Lean functionalities to the technical functionalities

In this step, we have added the Lean functionalities to make the system more performant by reducing time and non-add value operations.

Table 4.1 shows a part of the functional specifications document (FSD). It contains some examples of Lean functionalities.

Table 4.1 Functional specifications document (FSD)

			LEAN AND INDUSTRY 4.0	
FUNCTION	**Criteria**	**level**	**Functionalities**	**Parameters and tools**
FP1 Allow users to use the machine. FC5 Ensure the safety of users.	Safety Smart technology 4.0 Agility Human skills 4.0	Smartphone Cloud Application	Provide the communications between agents Enhance the human skills to use the new technologies of I4.0	Cyber security Cloud User satisfaction Digital student cards QR code
FP2 Allow machine to sort waste into three families: PET, LDPE, metal.)	Automation Availability Diagnosis Maintainability Self-cleanliness Smart technology 4.0 Support assistance	Panel of processed items From 33 to 50 cl (can, bottle) Material Detection Metals (Steel, Aluminum), PET (bottle), LDPE. Mixing rate of metal/plastic after treatment Time to change storage containers bottles and cans Cleaning time loading <5 min Error rate >80%	Reduce the six big losses Improve equipment efficiency Improve safety and workspace Provide the communications between agents Eliminate waste MUDA	Breakdowns, Setup Adjustment time Minor stoppages, Speed Down time Takt time Automation Automation Big Data Sensor Waiting time

		Volume after transformation <20% du initial volume		
FC1 Take into account the ecological aspect	Longevity	Electrical energy 220V Pneumatic power 6 Bar Volume > 30L per material Humidity Between 10 and 70% Temperature of standard room (between 12 and 25°C)	Reduce Emission Minimize material waste Optimize the choice of material.	Product life cycle Cost Pollution rate
FC2 Respect standards and laws.	Legality	Standards and Laws	Improve information visibility Use technology to support people	Standard Visualization
FC3 Allow machine to have the necessary information .	Communication	Big data Cloud system Internet of things	Provide the communications between agents.	Communicatio n Just in Time
FC4 Respect buildings and structure.	Accessibility Sustainability	Capacity Volume Evacuation Standard Dimension Laws 700mm*860mm*1700mm	Minimize of waste Easy to use	Surface Human skills

Step 5. Search solutions

By using the FAST (Function analysis system technique) diagram, several solutions were proposed. The solution considered by us has been chosen according to the Lean functionalities.

The connection between the agents has been carried out thanks to the implementation of an information alert system.

The technical solutions we have chosen based on Lean functionalities are:

- For the sorting system (Figure 4.3):

Nowadays, to sort the different types of wastes and plastics, industries use an electrified conveyor belt system. Indeed, the different cans and bottles are placed on a moving electrified belt. The aluminum cans are attracted by a magnet situated over the belt, and they will fall in the right box. The bottles will keep on going on the belt until a referral system will direct the bottles in different adapted boxes.

For that, following Lean and I4.0 functions and tools, we have chosen for the sorting system a conveyor, which composed of a recognition system with a barcode, and with two secondary belts inclined. The utility of this system is to recognize the object that the user threw away in the system. If the barcode is not able to read or if the label is missing, then a material sensor will determine the type of material, which prevents a mix of materials in the storage at the end of our system.

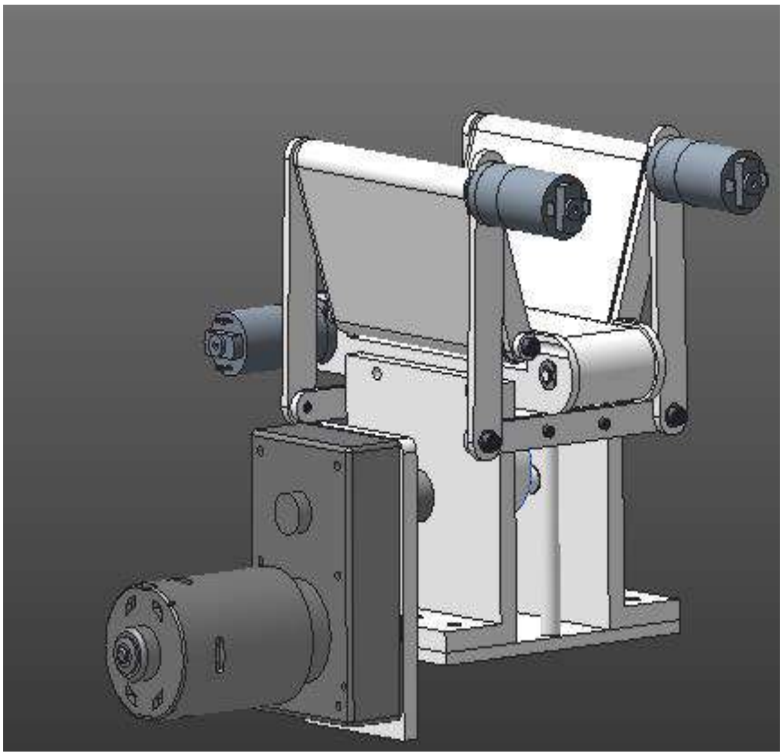

Figure 4.3 Sorting system

- For the crushing system, which is located just after the sorting system (Figure 4.4):

Existing solutions for crushing cans such as pneumatic or hydraulic cylinders are fast and efficient. But, they are not convenient to the list of performance criteria and Lean functionalities.

Pneumatic cylinders cause noise that is harmful to the user.

The hydraulic cylinders are used at very high pressure without value add for our system. Besides, this would have created more sealing problems.

For that, a suitable Lean solution is a grinding process using a trapezoidal screw. It is a system driven by an electric motor that transmits a rotational movement to this screw. In its turn, this screw will then rotate in a threaded hole to create a translational movement for a part that will crush the can. This process allows to crush and store cans. When the sorting system detects a can, it will send it to the crushing system. The can will arrive in the inlet. Then, it will fall in the blue part. The blue part is pushed until a location to crash the can. Then, the blue part comes back to get another can, and when it returns to the crushing location, it pushes the former can in a pipe that leads to the storage box.

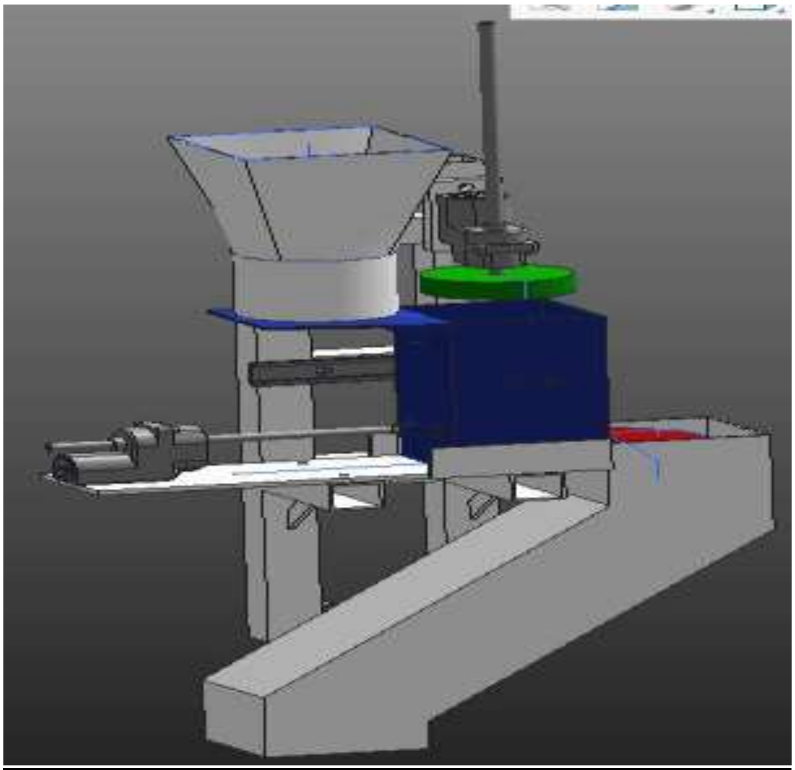

Figure 4.4 Crushing system

- For the grinding system (Figure 4.5):

The Lean solution is a one roller grinder. The system can also be open easily to do the maintenance works. To avoid the spillage of liquids from the remaining cans and buttons, thus causing soiling and system shutdown, an automatic cleaning system has been added with a tank that empties the conveyor belt and keeps it clean.

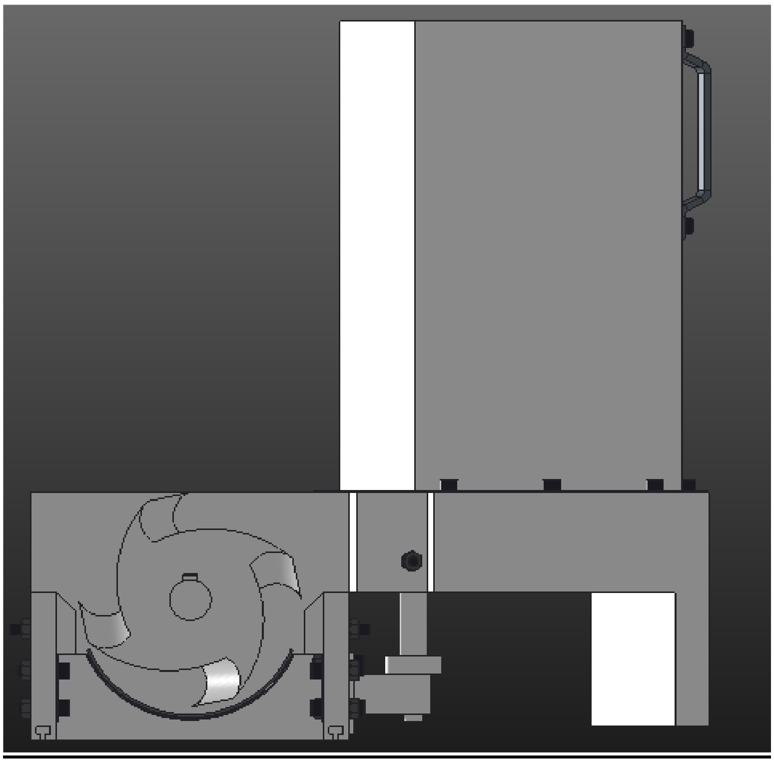

Figure 4.5 Grinding system

Step 6. Apply IDM to find innovative solutions

In this study case, we did not have a problem with contradictions between the criteria. So, we did not need to use IDM.

Step 7. Follow Lean Check-list Evaluation

In this step, we have checked whether all the required Lean functionalities are taken into account during the design work.

Figure 4.6 shows the final model of the system.

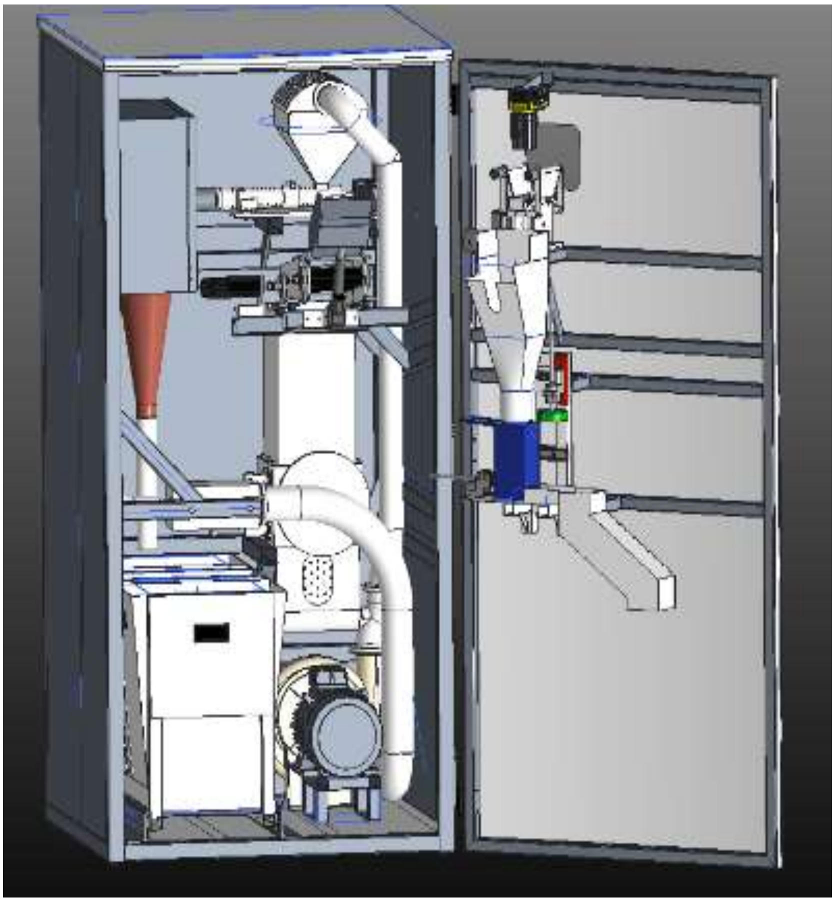

Figure 4.6 Final system

4.3 Case study 2: 3D printer clogged nozzle

To show the usefulness of IDM, we applied the Lean-System-Design approach to pedagogic case use.

Our Fablab laboratory contains six 3D printers that are used for different missions to design and prototype products. These 3D printers are in line with other machines (laser cutting machine, Strato design machine, etc.).

In this platform, we manufacture products composed of several components, made from several raw materials, then assemble them and finalize them.

In this environment, we have a recurring problem, which is the clogging of the print nozzle. The material continues to enter but could not go out, which causes other problems, such as the blocking of the material during the routing thereof. Our 3D printing does not detect when the nozzle is clogged. Other 3D printer machines detect this phoneme.

But in both cases, this maintenance problem requires periodic cleaning and loading the nozzle too often. Cleaning operation from a point of view of Lean must be performed when the 3D printer is stopped, so it is an internal operation.

The question that can pose is: How to clean the nozzle without stopping the machine?

To answer this question, we are looking to apply the steps of our approach to redesign the wire feed systems of the 3D printer to make cleaning operations external (can be done without stopping the printer).

To improve machine performance, we can use:

(1) The SMED method to reduce the changeover time of cleaning of the nozzle.

(2) The 5S method to facilitate the cleaning or the replacement of the clogged nozzle.

In this study, we integrate the SMED and 5S functionalities to reduce the printer downtime needed to clean the nozzle or make it possible while the 3D printer is running.

In the following, we present step by step the application of our approach on this 3D printer:

- In step 1: Regarding the feedback collected from user experience, we have defined all specifications demanded by the client (we listed all the technical functions of the 3D printer).
- In step 2, we provided functional analysis.
- In step 3, we selected the required performance criteria:

  Reliability

  Safety of operator

  Productivity

  Cost
- In step 4, we have seen that consider SMED and 5S functionalities could be helpful to take into account these criteria.
- In step 5, we listed all the solutions that we found.

The current solution on the machine (cleaning at the stop) can guarantee the user's safety. However, to clean the nozzle, the 3D Printer should be stopped, which harms productivity. In this case, the safety of the user is ensured but not productivity.

An automated solution exists on other machines, do the cleaning automatically (heat the nozzle or blow air into it to clean it). In this case, productivity will increase (automatic cleaning time). However, it is performed in masked time while the machine is running. Safety is ensured because the user does not interfere with the 3D Printer. Perhaps, these types of solutions need to add some systems to the machine such as a heating system or blowing air system, which are too expensive and can change the machine's range. Therefore, these solutions do not meet the criterion of "Cost", and there is no solution area. As a result, there are contradictions between the chosen criteria: "Safety", "Productivity", and "Cost".

We have seen that considering the SMED and 5S could be useful to take these criteria into account, but integrating these functionalities did not resolve the contradictions.

- Thus, in step 6, we use IDM to find innovative solutions.

We aim to convert the "Clogged nozzle" problem into an external operation, which can perform when the 3D printer is running. To solve this problem, we have formulated all the problem data. In Figure 4.7, the problem graph serves to identify the problems and partial solutions. We started with forming our initial problem of the "Clogged nozzle". Then, we look for the effects of this initial problem in terms of partial solutions, and thus the other problems that can be generated by the partial solution.

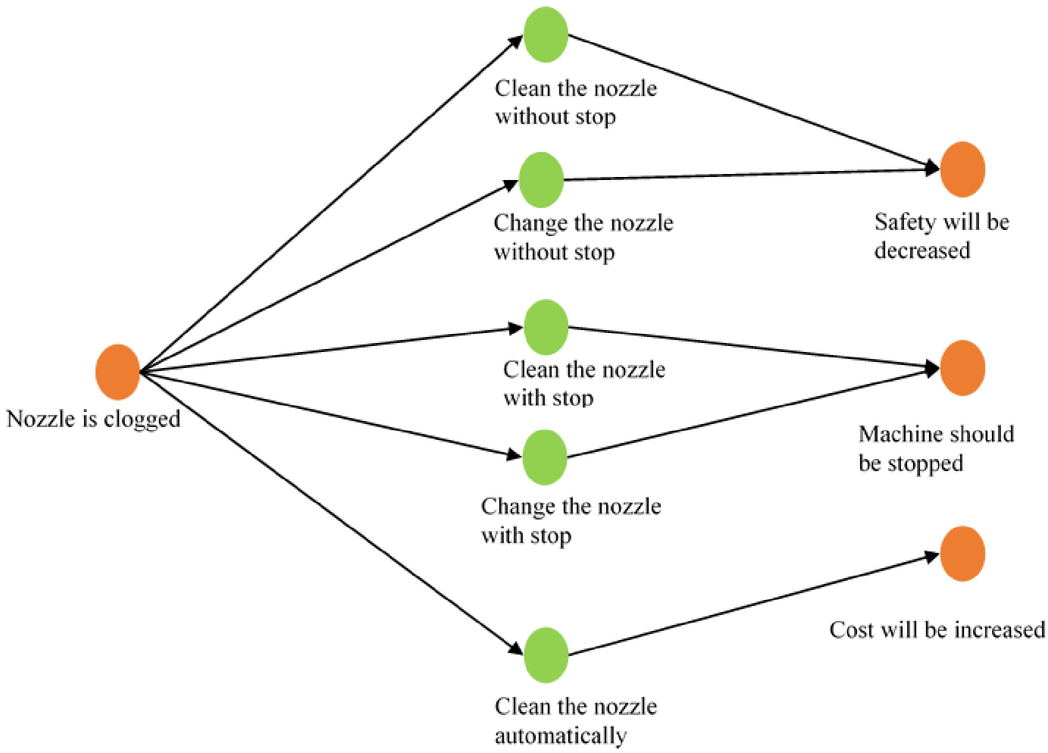

Figure 4.7 Problem graph of the clogging of the nozzle

We formulate the contradictions for all the problems illustrated by the problem graph. For this purpose, we used the poly-contradiction template to show the relationship between evaluation parameters (the parameter that allows us to evaluate a criterion) and action parameters (the parameter that machine or user has to do to improve evaluation parameters) (Table 4.2).

We made correspondence between TRIZ evaluation parameters and our chosen criteria.

We used "Productivity" for the "Machine operating or stopping time" problem because if the "Machine stopped" the time of producing the output of the system will increase, so its productivity will decrease.

Furthermore, we allocated "Reliability" to the problem of the "Nozzle is clogged" because this problem can decrease the ability of the system to perform its intended functions predictably.

In the same way, we applied the evaluation parameter "Objected-generated harmful factors", which means that the system has a harmful effect to describe the safety of the operator.

Besides, "Extent of automation" means that the machine needs a supplementary automatic system to perform a function without human intervention, which increases the cost.

It is a choice taken from an analysis of the TRIZ evaluation parameters.

Also, we believe that the integration of Lean from the design phase could concern criteria intrinsically to the system and that the designer is supposed to have acquired.

Of course, a parameter such as "Maintainability" can also address the problem as an example. But we preferred "Reliability" because we have seen in this case that the "nozzle clogged" is related to the capacity of the system to perform its intended functions predictably. But also to ensure the link with the TRIZ parameters.

A clear linkage between the TRIZ parameters and the performance criteria can remove ambiguity for the designer.

In our case, for each action parameter, we have attributed one contradiction.

For example, as shown in Table 4.2, the action parameter "Clean the nozzle without stop" causes one contradiction between "Productivity" and "Objected-generated harmful factors".

Table 4.2 Table of Contradictions

Evaluation parameters	**Action parameters**	
	Clean the nozzle without stop	
	Yes	No
Productivity (The machine operating time)	☺	☹
Objected-generated harmful factors (User Safety)	☹	☺
	Change the nozzle without stop	
	Yes	No
Productivity (The machine operating time)	☺	☹
Objected-generated harmful factors (User Safety)	☹	☺
	Change the nozzle without stop	
	Yes	No
Productivity (The machine operating time)	☺	☹
Reliability (Clogging problem)	☹	☺
	Clean the nozzle with stop	
	Yes	No
Productivity (The machine operating time)	☺	☹
Reliability (Clogging problem)	☹	☺
	Clean the nozzle automatically	
	Yes	No
Productivity (The machine operating time)	☺	☹
Extent of automation (The cost of the production machine will be increased)	☹	☺
Definition of the TRIZ parameters		

- **Productivity: The number of functions or operations performed by a system per unit time.**
- **Objected-generated harmful factors: The harmful effects that are generated by the object or system.**
- **Reliability: System's ability to perform its intended functions.**
- **Extent of automation: The extent to which a system or object performs its functions without human interface.**

After formulating the contradictions, it was necessary to evaluate these contradictions to choose the most important one that eliminates the problem situations.

This task, performed by the designer, depends on his experience and his knowledge, and also the order of priority of the criteria.

In this way, we selected the contradiction between "Reliability" and "Productivity" when the action parameter requires to stop the machine. To solve the selected contradiction, we propose to apply the contradictions matrix. The inventive principles will help us to obtain the final solution. The following table 4.3 is part of the contradictions matrix, which suggests the following principles: 1. Segmentation, 35. Parameter change, 29. Pneumatics and hydraulics, 38. Strong Oxidants.

Table 4.3 The proposed principles in contradiction matrix

	Worsening feature / **Improving feature**	**Weight of moving object**	**…**	**Productivity**
		1	…	39
1	Weight of moving object			35,3 24,37
…	…			
27	Reliability	3,8 10,40		1,35 29,38

Then, we should analyze the proposed principles to understand which of them could help us more to solve the problem. As you see in table 4.4, the first principle is number 1 or "Segmentation", which means, "Divide something into smaller pieces to receive a new valuable piece of innovation".

This principle is divided into the following sub-group:

- Divide an object into an independent part.
- Simplify the assembly and disassembly of an object.
- Enhance the degree of segmentation in an object.

Principle number 1 could help us to receive the solution "the feeding system in sort to design two nozzles to be mounted and independent of each other". The user cleans one nozzle when the other is in use.

The cleaning operation follows the 5S steps to avoid the waste of time and can be performed in masked time. This solution was in the field of our laboratory competency.

The other proposed principle by the contradiction matrix is principle number 35 or Parameter change, which includes the following sub-group:

- Change the physical state of an object into gas, liquid, or solid.

- Modify the concentration or consistency of an object.
- Improve the degree of flexibility of an object.
- Modify the temperature.
- Change the pressure or other parameters.

By inspiring from this principle, we could propose a solution to change the type of material used by the machine by changing the characteristics of the material to prevent clogging of the nozzle. But, this solution was out of the capacity of our laboratory.

Furthermore, it could also be inspired to solve the problem by increasing the temperature of the nozzle. However, this solution would increase the cost of used energy by the machine.

Table 4.4 also shows the number 29, which is "Pneumatics and Hydraulics". This principle proposes to use liquid or gas parts, instead of the solid parts of the object. This principle could not help us to obtain a solution to our problem because a compressing system is also expensive.

The last suggested principle by the contradiction matrix is number 38 or "Strong Oxidants".

In this principle, we could find the following sub-principles:

(1) Use oxygen-enriched air instead of common air.

(2) Use pure oxygen instead of enriched air.

(3) Expose Oxygen to ionizing radiation.

(4) Use ozone instead of oxygen.

The principle "Strong oxidant" also, like principle number 35, could give the concept of changing characteristics of the material by adding some other gas to make a chemical reaction to minimize clogging phenomena in the nozzle or to solve material in the nozzle.

However, the proposed solution by this concept also could not be in the scope of our laboratory.

Table 4.4 Comparing of the proposed solutions

Principles in contradiction matrix	**Cost of solution for the user**	**Capacity of our laboratory to develop the solution**	**Total**
Principle 1 :Feeding system in sort to allow the two nozzles to be mounted and independent of each other	2	3	5
Principle 35: Changing the type of material, which is used in the machine or Increasing the temperature of the nozzle	2	1	3
Principle 29 use liquid or gas parts instead of solid parts of the object	1	3	4
Principle 38 : Strong Oxidants use chemical reaction to prevent drying material in nozzle	1	1	2
Point 0 Minimum **Point 3 Maximum**			

At the end of the process, we should select one of the proposed solutions to solve the problem.

By looking at the analysis performed in the previous step, we choose this solution:

"The feeding system in sort to allow the two nozzles to be mounted and independent of each other", inspired by the segmentation principle.

This solution was to redesign the feeding system. When a nozzle is clogged, the system allows the use of the other one. These allow the two nozzles alternately extrude, and thus to be able to replace the work of the clogged one that either will be changed or cleaned in masked time following the 5S steps.

Once the solution is analyzed, the modern CAD design systems and the CAE systems will be verified and applied to validate the case study.

4.4 Case study 3: Agile digital tool for convenience stores

In this project, we applied our design approach to a service system to create a digital tool that could help the convenience store to cope with the e-commerce. Our objective is to validate the feasibility of our proposal on the design of service systems.

This project aims to create a tool to put people in contact with local shops. The tool will be able to identify the needs of the consumers; then connect the prospect with the corresponding shop.

It is a partnership project with CSIP/ICUBE and an industrial partner company that we cannot mention by name for confidentiality reasons.

The digital solution and computer data corresponding to develop the software are confidential and belong to the industrial company.

In the following, we present a general part of the work, which was carried out to illustrate how our "Lean-System-Design" has led to design results that meet the specifications of the project.

4.4.1 Application of Lean-System-Design

Step 1. Define all specifications demanded by the client

The project had different missions.

To collect the requirements, needs, and concrete problems of both the local shops (conveniences stores) and the consumers, the team had two main missions:

(1) Analyze the literature on the convenience store's works, their existing problems, and their digital models, if they exist, and these existing consumer models.

(2) Complete the first analysis by a survey and interview convenience stores (local stores) and consumers.

This allowed us to:

- Identify the actors and their different needs (convenience stores, customers, provider services, etc.).
- Identify the barriers preventing the integration of digitization into the routine of convenience stores.
- Gather information on the convenience store’s quotidian workload.
- Identify consumer models (lifestyle, psychological, economic, social, etc.).
- Identify the relationships and links between the actors in terms of functions and contradictions.

Figure 4.8 shows us the purpose of the project and the main actors.

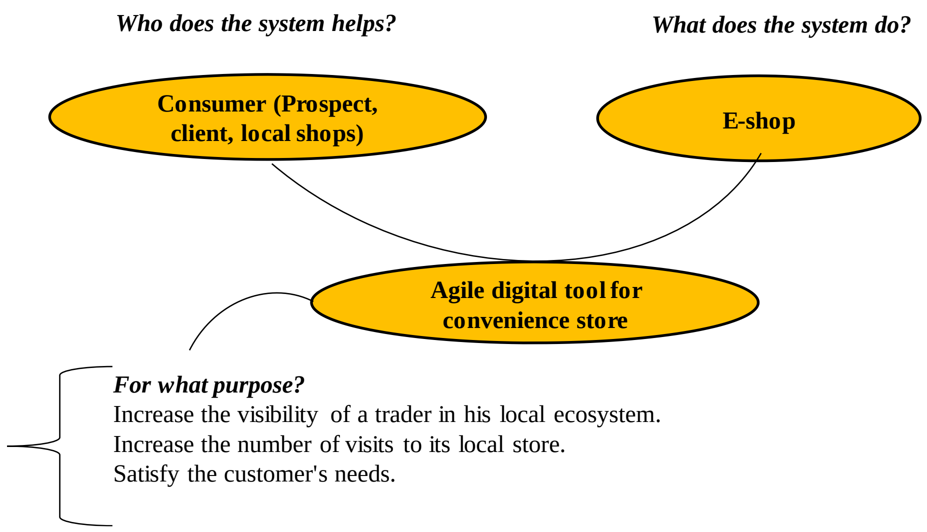

Figure 4.8 Identification of the actors of the project

Step 2. Provide functional analysis

The main functions of the project are as shown in Figure 4.9:

Primary Functions:

FP1 Allow consumers to purchase their needs from a local shop, using a maximum of selecting criteria

FP2 Allow local shops to present the products online in a way that is visible to consumers.

Constraint Functions:

FC1 Be agile (could be updated quickly and easily).

FC2 Ensure user security.

FC3 Reduce waste inadequacy with the environment.

FC4 Ensure consumer behaviors.

FC5: Do not increase the workload of convenience store operators.

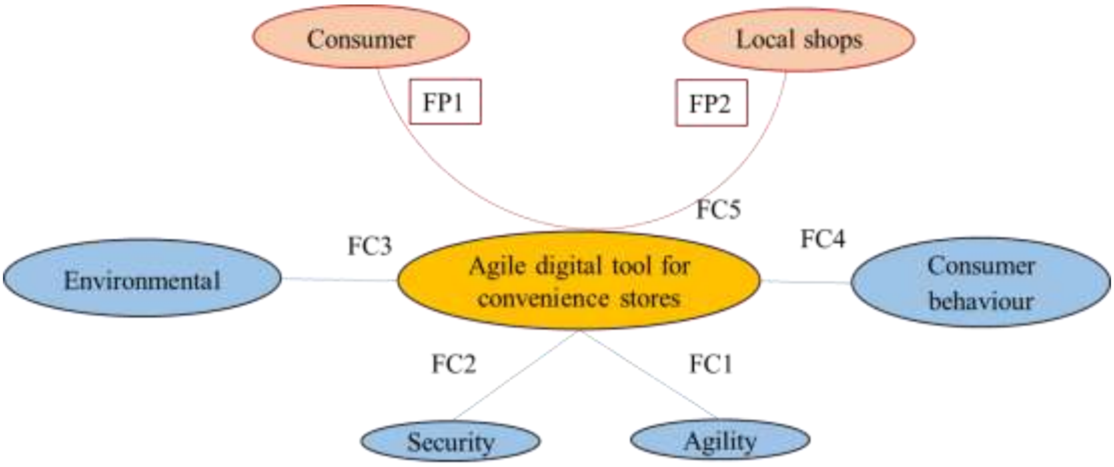

Figure 4.9 Octopus diagram

<u>Step 3. Elaborate the list of criteria regarding the constraints and the objectives</u>

The most required performance indexes will be the criteria that guarantee:

- Agility: Create e-commerce that satisfies the needs of consumers with its local shops easily and quickly.
- Automation: Automate a lot of tasks that can be performed by the system without human intervention.
- Complexity: Decrease the complexity of systems, functions, and tasks.
- Smart technology 4.0 and Human skills 4.0: Use the new technologies to informs managers about all data concerning their stores, number of visitors, etc.
- Processing: Enhance the speed of exchange of information.
- Security: Guarantee the security of the website user (fraud, payment cards, traffic, etc.).
- Sustainability: Reduce all types of wastes inadequacy for the environment and the store management.
- Supplier and customer integration and user satisfaction: Exchange in real-time all information related to purchase, sale, and delivery to guarantee consumer and buyer satisfaction.

<u>Step 4. Add Lean functionalities to the technical functionalities</u>

Table 4.5 shows both the technical functions and the appropriate Lean functionalities of the system.

Table 4.5 Functional specifications document (FSD)

Criteria	Comercial functionalities	Lean functionalities	Lean parameters
Agility and Processing	Create an e-shop	Eliminate all type of wastes. Provide the communications between agents.	Time to fulfill a purchase Waste elimination
Automation	Minimize the human intervention.	Automate tasks.	Automate solutions
Complexity	Decrease the complexity	Simplify tasks Excite opportunities for solving complex problems.	Number of tasks Visibility Perform tasks in parallel
Smart technology 4.0 and Human skills 4.0 Security	Make system agile, smart, and easy to use.	Use technology to support people. Make the system easy to use. Enhance the performance of system by adding the new technologies of I4.0.	Big Data Cloud computing Internet of things Cyber security System integration
Sustainability	Respect environment	Reduce all type of wastes inadequacy for the environment Improve Social Human Skills Improve the efficiency of system and equipment	Elimination of Waste
Supplier and customer integration and user satisfaction	Exchange all information related to purchase, sale, and delivery to guarantee the consumer and buyer satisfaction.	Provide the communications between agents. Make decisions autonomous and in real time. Adapt quickly to a changing demand	User satisfaction

<u>Step 5. Search solutions</u>

A complete study of the markets, the consumers, and the local shops were carried out to find out their needs, problems, and wishes.

And thus, a review of the literature of convenience stores, consumer models, and E-commerce, brainstorming sessions, interviews with consumers and local shops have already been carried out.

To classify all this data, a few engineering methods have been used, such as the Ishikawa diagram, FMECA analysis, the 5 whys, SWOT, and FAST diagrams to visualize the problems and their degree of criticality for each possible solution.

During this step, many meetings took place between the different team members to present all the possible solutions to respect all the criteria mentioned above to choose the most appropriate solution for our project.

Step 6. Apply IDM to find innovative solutions

After the analysis of the two existing classical solutions performed in the previous step: "Use third-parts e-shops" and "Create their own e-shops".

IDM is applied to formulate the problems to solve the contradictions.
The graph problem in figure 4.10 shows that there are contradictions between the visibility of the convenience store and the complexity and cost when creating the convenience store's website, and between visibility and trust, speed, and cost in case of the use of an intermediate e-commerce website by the store.

We see that using third-part e-commerce may help to find goods by consumers, but this will increase the cost of goods and decrease the trust because consumers don't know the seller, and the delivery time will also increase.

And, the creation of the own website will also increase the complexity for the consumer to find it, which he is not used to using.

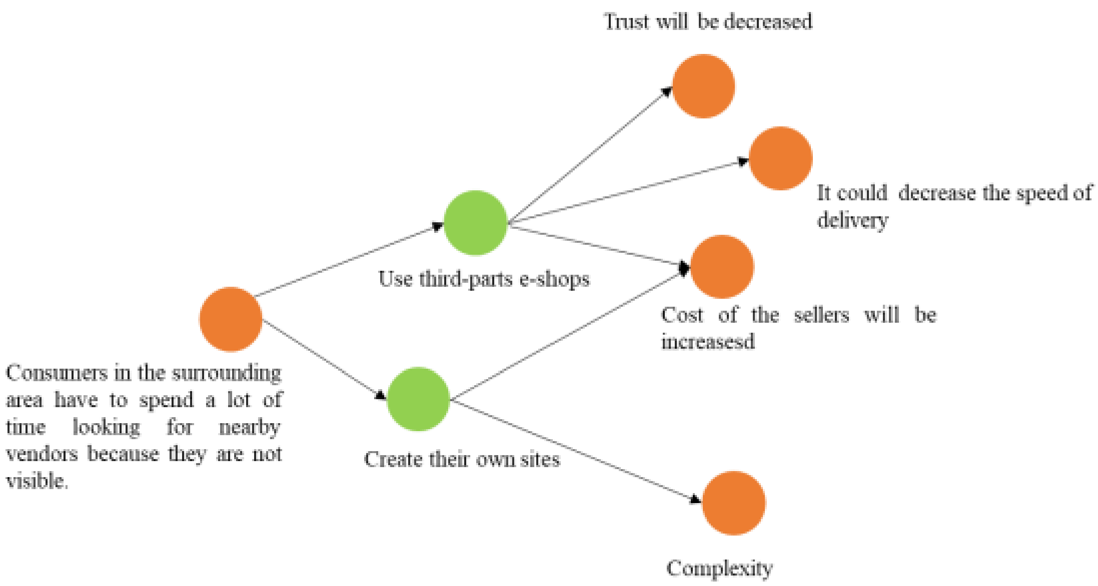

Figure 4.10 Problem graph

In the table 4.6, the tables of contradictions have been formulated.

Table 4.6 Table of Contradictions

Evaluation parameters	Action parameters	
	Create the own site	
	Yes	No
Loss of time	☺	☹
Cost of the sellers	☹	☺
	Use the third parts e-shops	
	Yes	No
Loss of time	☺	☹
Cost of the sellers	☹	☺
	Create the own site	
	Yes	No
Loss of time	☺	☹
Complexity	☹	☺
	Use the third parts e-shops	
	Yes	No
Loss of time	☺	☹
Speed	☹	☺
	Use the third parts e-shops	
	Yes	No
Loss of time	☺	☹
Trust between seller and consumer	☹	☺
Definition of the TRIZ parameters		

- **Loss of time: It is the time lost due to activities with no added value.**
- **Speed: It is the speed to get the service by consumers from sellers.**
- **Complexity It is the degree of complexity in using the service.**
- **Trust: It is the trust between seller and consumer.**
- **Cost: It is the cost of service.**

So, we have used IDM to solve the contradiction between the requirements functions and the Lean functionalities to add more and mora criteria.

4.5 Conclusion of this chapter

The proposed examples validate the feasibility of our proposed approach to machines and also a service system.

The application of the proposed approach allowed us to provide some more performant solutions integrating Lean functionalities.

Unfortunately, the selected steps, calculations, and results of the first and the third projects do not show in detail due to confidentiality.

The application of our approach is applied manually. We used many tables to capitalize on the data. It is quite long and not easy to apply.

Despite this, we have demonstrated the feasibility and usefulness of the approach clearly and understandably for the reader.

We seek to validate the method on a more complex and complete real industrial case.

To put our approach into practice, we began the first steps in Chapter 5 for implementing a CAD software module to support the integration of Lean functionalities from the design phases.

Chapter 5. Lean-System-Design software specifications

5.1. Introduction

In the two previous chapters 3 and 4, we presented our Lean-System-Design approach of integrating Lean functionalities from the early design phases in an Industry 4.0 context. Then we validated the feasibility of our proposal through 3 case studies.

In this chapter, we propose the software specifications of integrating Lean functionalities from the design phases.

We present successively the module specifications, the module architecture, then the UML analysis diagrams: object, use case, class, activity, and communication.

5.2. Specifications

We decide to implement the Lean-System-Design approach to integrate it as a module into CAD software. We called it Lean-System-Design (LSD).

As we explained in chapter 3, our Lean-System-Design approach consists to integrate the Lean functionalities to carry out the function specifications, which helps the designers to take into account the maximum of the performance criteria to satisfy all the functional, use, and performance requirements.

For that, the data of the list of criteria, the appropriate Lean functionalities, and Lean parameters should be provided to the designer, additionally to the design methods (FAST, IDM, Task Decomposition, etc.) to carry out the initial, conceptual, and detailed functional specifications.

5.3. Architecture

The architecture of the modeling targeted in our methodology consists of four parts (Figure 5.1):

(1) In the requirements list, the designer collects all the specifications of the system.

(2) The design center covers functions and tasks.

(3) In the Lean Centre, the designer uses the list of criteria suitable for the requirements, accompanied by the appropriate Lean functionalities and

parameters.

Thanks to this Lean center, the designer can optimize all solutions, from the technical and socio-technical tasks, the internal and external tasks.

(4) In the IDM center, the designer can use the IDM to find solutions more suitable for the chosen criteria and Lean if the solution set is null.

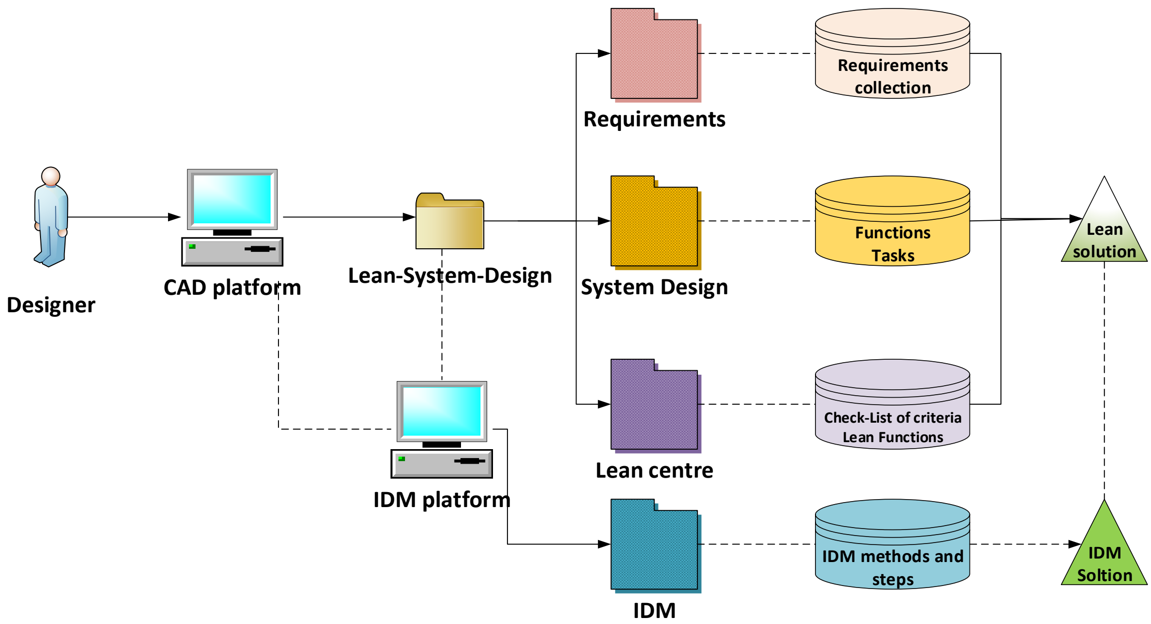

Figure 5.1 Architecture of our model

5.4. UML diagram

We use the ''Unified Modeling Language'' (UML) (Booch, Rumbaugh, and Jacobson 2000) to build our system model.

5.4.1. Object diagram

In this section, to better understand the system modeling, we precise the objects of the Lean-System-Design module.

Our system modeling depends on the user (Design team, engineers) that reacts with the CAD platform to design a complex system. For that, it is crucial to precise the classes of our system into (Figure 5.2):

External classes:

- Designer, Engineer team, etc.

- CAD platform.
- IDM platform.
- All documents that the designer enters into the LSD module (Requirements collection, etc.)

Internal classes:

- List of criteria.
- List of Lean functionalities.
- All methods of Design, which can be used by designers to follow each step of the Lean-System-Design approach (Functional specification, FAST, SADT, IDM, etc.).

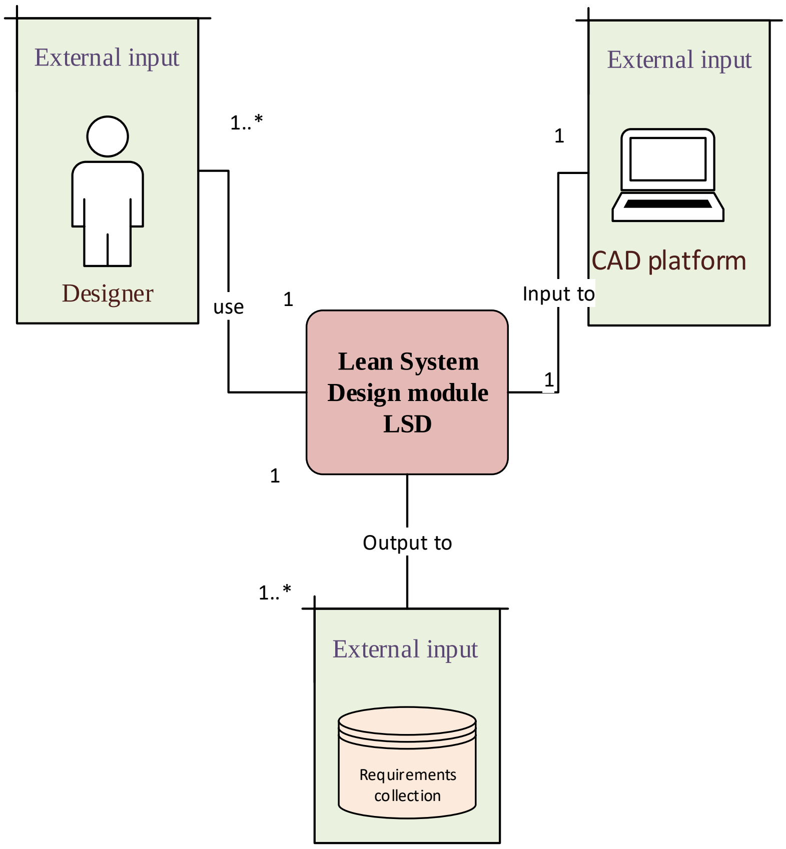

Figure 5.2 LSD module context

The object diagram in Figure 5.3 presents our four interface objects associated with the system. For example, if the customer requests an environmentally and friendliness system, this is an external output. The criterion of "Sustainability", the appropriate Lean functionalities, and the data of examples of Lean and IDM solutions are corresponding to the internal output.

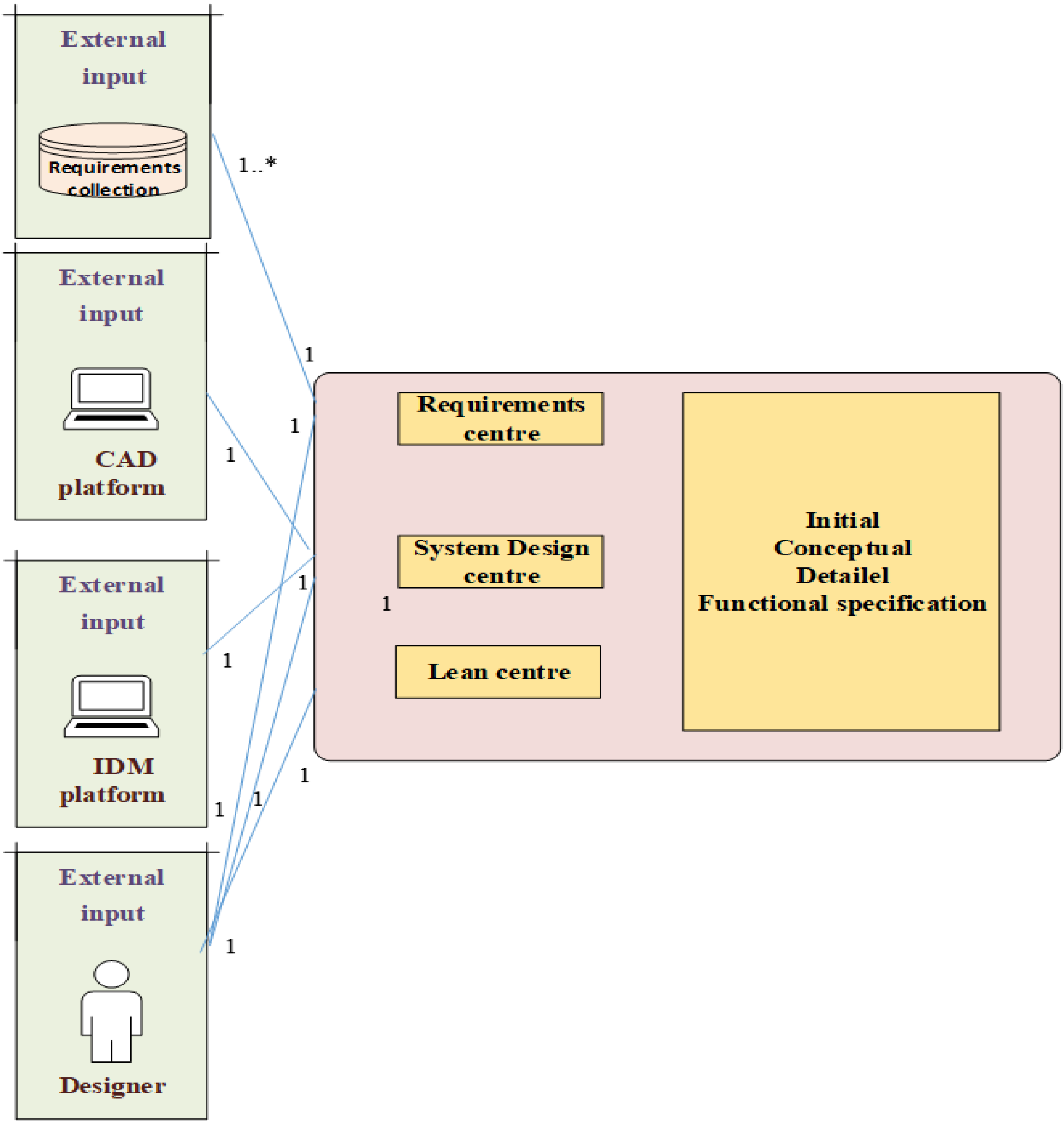

Figure 5.3 Object diagram of LSD module

5.4.2. Use case diagram

LSD allows the designer to apply our approach by providing him all information and methods that needs to design his system.

To understand our system, the use case model in Figure 5.4 contains all information that covers the three initial, conceptual, and detailed functional specifications according to the list of criteria and Lean functionalities:

(1) Function components, function, and sub-functions, definition, and their decomposition.
(2) List of criteria.
(3) The appropriate Lean functions (functionalities) and parameters.

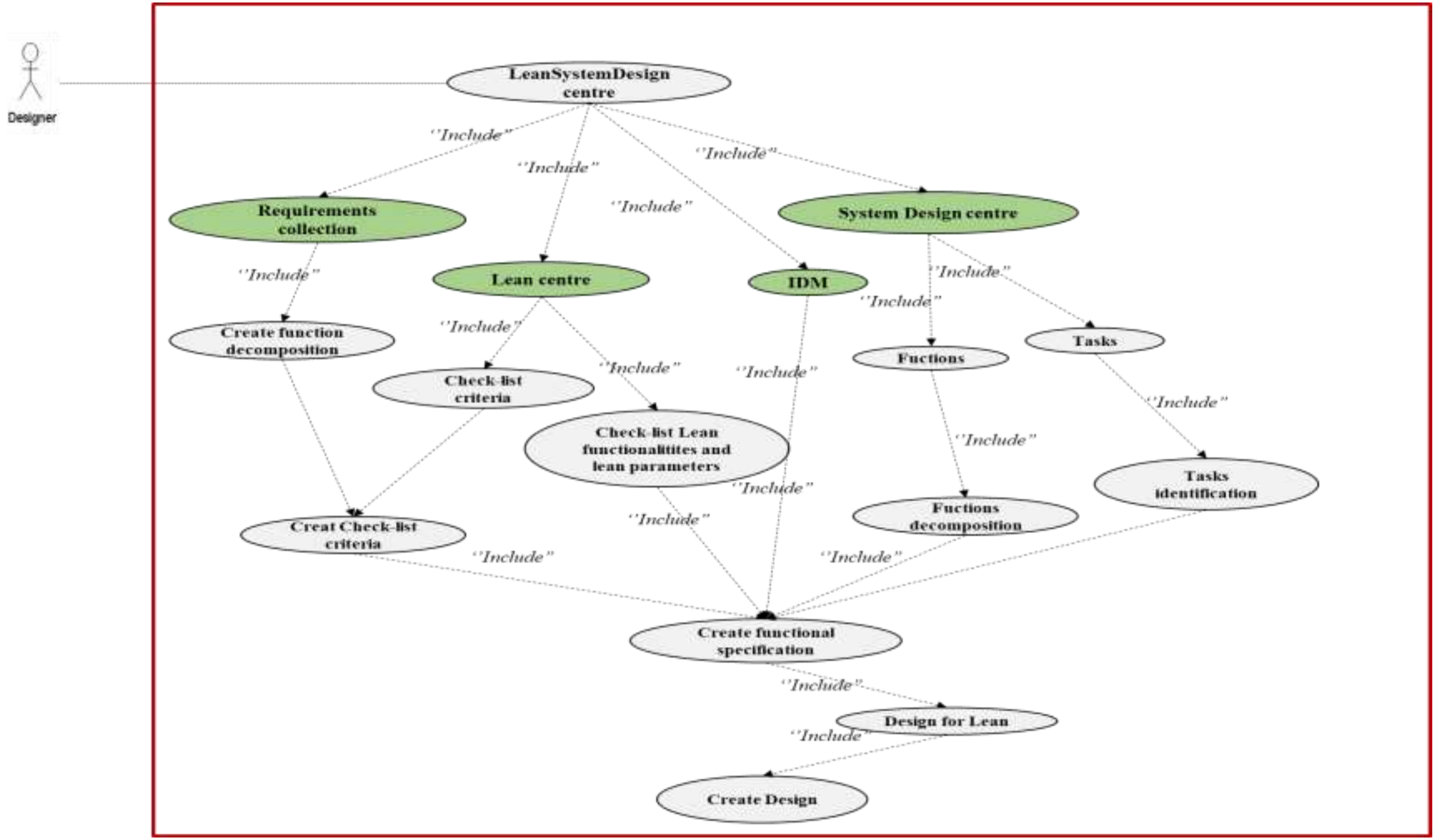

Figure 5.4 Use case diagram of LSD module

5.4.3. Class diagram

The static model was developed by the class diagram to clearly show the LSD module (Figure 5.5).

The model is presented as the connection of the different classes corresponding to the different aspects of the LSD module.

Class diagrams are helpful to precise classes, their attributes, operations, and relationships between objects in the LSD module.

Therefore, the Class diagram provides architectural modeling for the implementation of the system.

5.4.4. Activity diagram

Figure 5.6 shows the activity diagram of our LSD module, representing the dynamic aspects of our module.

The diagram illustrates the description of the LSD module when used.

It explains the different scenarios that the designer will face when designing a system.

The designer can use the LSD module while drawing on the CAD platform.

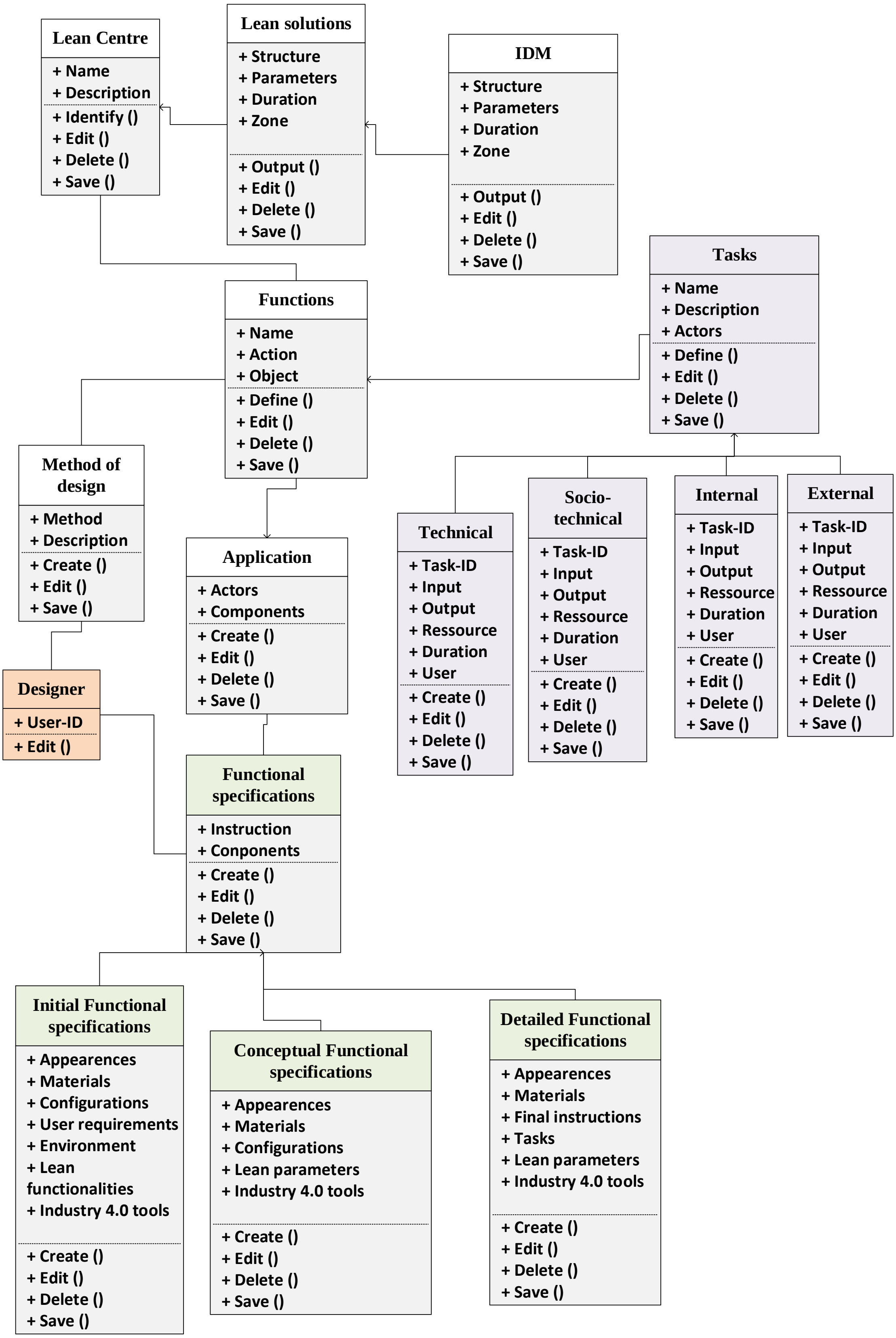

Figure 5.5 Class diagram of LSD module

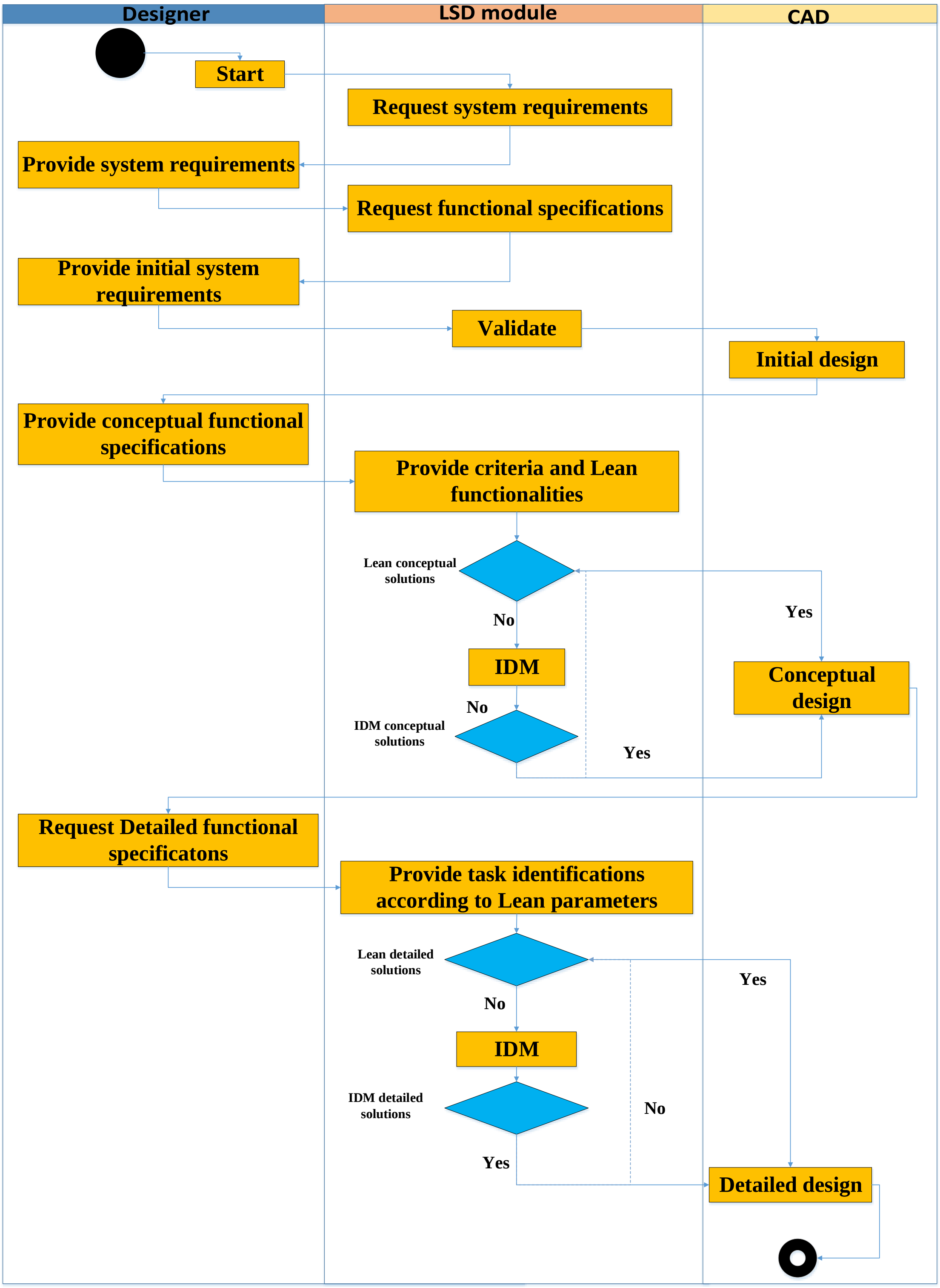

Figure 5.6 Activity diagram of LSD module

5.4.5 Communication

Communication refers to:

- The interaction between elements.
- The communications occur between objects.
- The messages that circulate between them emphasize the relationships between classes.

Following the class diagram, we present the communications that occur:

(1) Interacts with: After task assignment, designer first interacts with CAD interface.

(2) Clicks: Designer clicks System Design Centre button.

(3) Clicks: Designer clicks Function Level button and enters the Function Level interface.

(4) Shows: Function Level interface is shown.

(5) Inputs Function: Designer inputs the data (from customer or other resource) and all other requirements to create function.

(6) Creates: Designer creates Initial functional specification, and then saves and exits.

(7) Clicks: Designer clicks Lean-System-Design Centre button and enters Lean Centre.

(8) Shows: Performance criteria and the appropriate Lean functionalities interface is shown.

(9) Clicks: Designer clicks lean Function Level button and enters the lean Function Level interface.

(10) Shows: lean Function Level interface is shown.

(11) Inputs operation: Designer inputs the data to create function tree according to initial functional specification Lean functionalities and parameters button.

(12) Inputs operation: Designer use Lean parameters for each one.

(13) Clicks: Designer clicks System Design Centre button, and then clicks Task Level button and enters the Task Level interface.

(14) Shows: Task Level interface is shown.

(15) Clicks: Designer clicks Lean-System-Design Centre button and enters Lean Centre.

(16) Shows: technical Centre, socio-technical center, internal and external center interfaces are shown.

(17) Clicks: Designer clicks technical Centre, socio-technical center, internal and external center interfaces.

(18) Inputs operation: Designer inputs the data to carry out the task definition and planning according to the performance criteria and the appropriate Lean functionalities.

(19) Clicks: Designer clicks Lean-System-Design Centre button and enters IDM.

(20) Shows: IDM interface is shown.

(21) Inputs operation: Designer use IDM to solve contradiction

(22) Creates: Iterative operation to create the Conceptual functional specification according to the task planning.

(23) Clicks: Clicks Lean System Centre button, and then clicks Lean functionalities and parameters button and Industry 4.0 principles. And enters Lean functionalities and parameters, and Industry 4.0 principles.

(24) Shows: Lean functionalities and parameters, and Industry 4.0 principles interfaces are shown.

(25) Inputs operation: Designer defines the Lean parameters of internal task, external task, technical task and sociotechnical task.

(26) Inputs operation: Designer use Lean parameters

(27) Inputs operation: Designer estimates the best possible solution that satisfy the all criteria performance.

(28) Input: Designer creates the parts and components in CAD software for each technical task.

(29) Clicks: Designer clicks Lean System Centre button and enters Lean System Centre.

(30) Shows: IDM interface is shown.

(31) Inputs operation: Designer use IDM to solve contradiction

(32) Creates: Iterative operation to create the Detailed functional

We have presented the general structure of the LSD module.

The next step is to convert the UML models to the CAD modules through programming.

5.5. Conclusion of this chapter

In this chapter, a graphical representation of the LSD module has been presented to transform our Lean-System-Design approach into a useful tool to facilitate the work of the designer.

We have shown the first step of implementing Lean-System-Design in CAD software. The Use case, the Class, and the Activities diagrams of the Lean-System-Design module were drawn by UML. We have also provided communication for the module.

Unfortunately, UML models are not yet converted into CAD modules by programming. That will be our future work.

We prefer to remove all obstacles and limitations related to our approach to reduce the designer's workload before moving on to the IT development part of the LSD module. For example, the linkage between TRIZ and Lean evaluation parameters enables the system to select the right choice but not the designer.

Chapter 6. Conclusions and perspectives

The purpose of this thesis is to offer designers a support approach and tool that can be helpful to design a performant system from the early design phase with minimal needs to use Lean tools in its use phase.

6.1. Contributions

We have positioned our study according to the works, which carried out in the same field of Lean Design, and we further have analyzed the literature on the integration of Lean from the design phases.

This literature review in Chapter 2 aims to highlight the design methods useful for Lean integration, and the interdependence between Lean and Industry 4.0 to understand the homogeneity between the two concepts to facilitate their integration.

For this, we have specified our complex system and these components to which our targeted methodology will react. Our system is complex, can be a production system, machine, and service system.

Then, we have provided the most famous existing design methods, which tend to increase system performance. And then, we presented a review of the literature about Lean integration from the design phases.

For this reason, we gave a general introduction to the concept of Lean, its history, principles, methods, and tools. We conclude that Lean plays a crucial role in increasing the system performance, not only in the use phase but also from the design phase, which we believe is the most appropriate choice. It can be useful for integrating performance criteria required to enhance the efficiency of complex systems by optimizing their components and their interactions from the early design phase in the context of Industry 4.0.

Our work is in line with current trends in Industry 4.0, so we have also presented a general introduction to Industry 4.0 to highlight its importance on system performance. Then, we studied the convergence and divergence of the two concepts, Lean and Industry 4.0.

We noted that Lean and Industry 4.0 could combine to design an optimal and modern production system.

In Chapter 3, we developed an innovative approach for integrating Lean from the design phases to have a performant system, which does not need to apply Lean in the use phase.

For this purpose, a survey was conducted to see how designers consider the conditions of use from the system design process. Then, we have analyzed the correspondence between Lean and Industry 4.0 to propose a method that goes with the current occupations of industries.

Then, we have analyzed the functionalities of Lean, identified, and classified them to determine which ones can be integrated from the design of production systems in the context of Industry 4.0.

A "Lean-System-Design" approach has been developed. It defines a systematic and detailed guide for the integration of Lean from the early design phase.

This Lean-System-Design approach is based on seven steps.

The designer defines all specifications demanded by the customer in Step1. In step 2, the designer provides a functional analysis to define technical functions, service functions, and constraints. In step 3, the designer elaborates on a list of criteria regarding the objectives and the constraints. In step 4, the designer adds Lean functionalities to the functionalities required by customers (technical functionalities). In step 5, the designer develops a solution to fulfill all required functionalities (technical functionalities and lean functionalities). In step 6, if the solution zone becomes zero, the designer uses the Innovative Design Method (IDM) to find an innovative solution. To avoid any missing, in step 7, the designer follows the Lean Evaluation Check-list before prototyping.

The two lists used in the approach are:

- List of criteria to perform the requirements of customer, standards, laws, environment, in the context of Industry 4.0.
- List of Lean functionalities derived from Lean principles, which helps to integrate these criteria.

This approach is developed to be applied to a production system or on industrial machines to minimize Muda and all types of waste, and to optimize their agents and their interactions.

To show the feasibility of our Lean-System-Design approach, we have applied it in Chapter 4 to three case studies.

The first one concerns the design of a waste treatment (waste-disposal) machine to highlight its advantages. The second one, which concerns the clogged nozzle of a 3D printer, discusses the usefulness of IDM to solve this problem by resolving contradictions that could be due to the integration of Lean functionalities. The third is to show that our approach can also use it to apply it to the design of service systems.

Consequently, to put our approach into practice, we have started in chapter 5 the first steps to implement a CAD software module to support Lean functionalities integration from the early design phase. We provided the specifications of the software to enable the integration of Lean functionalities in the design phase. We have presented specifications and UML analysis diagrams: object, use case, class, activity, and communication.

The graphical representation of the LSD module was drawn by UML to transform our Lean-System-Design approach into a helpful tool that can facilitate the designer's work.

6.2. Limitations

There are some limitations of the proposed Lean-System-Design, which can be improved to enhance the work and make it easier for the designer to use it.

These limitations were concluded from user experience when we applied our approach to the two case studies of the waste treatment machine and the service system.

The first limitation is that the approach adds Lean functionalities to the technical functionalities required by the client. So, it may increase the workload of the designer. For the moment, we did not evaluate the sequences of a new workload on designer productivity and motivation.

The second limitation may be that the designer, according to his knowledge, does not know how to choose the adequate Lean functionalities for his problem.

Lean functionalities do not provide the designer with the most optimal solutions. The generation of the solution concept is related to the methods and tools used by the designer, reflecting his knowledge and skills.

The third limitation is that some links between Lean functionalities and Lean metrics (parameters) are not provided, and between quantitative and qualitative Lean functionalities. The designer may have some difficulty establishing these linkages.

The fourth limitation is that the IDM based on TRIZ still not fully ready to solve a service contradiction for a service system.

Despite the presented applications in chapter 4, the effectiveness of our approach cannot be sufficiently guaranteed without the full development of a module and software to be applied to a complex production system.

6.3. Perspectives

Our method is the first approach and requires additional work to go beyond the limitations. This work is part of our research team in which some researchers are working to develop some steps to provide more details and thus facilitate the implementation of software that can be easy to use by the designer.

To overcome these limitations, future research will be adopted to improve more and more our approach.

To remove the ambiguity, we will classify the Lean functionalities into quantitative and qualitative design guidelines, which makes it easier for the designer to use the LSD module. We improve the list, which can be classified for each agent and interaction of the system.

We are on developing the concept of generating solutions for Lean functionalities from the design phases.

We continue the development of module CAD and software to apply to a complex production system. This software could make the linkages with these concepts to limit the choices taken by the designer himself. Artificial Intelligence and Machine Learning could be useful in this aspect. We will adopt a deep learning model to produce more Lean solutions.

Once the module or software is ready, we need to apply it to industries to test it and interview them to have feedback.

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Résumé de thèse en français

1. Titre de la thèse

Contribution à l'amélioration de la performance des systèmes de production et de service par la prise en compte les principes de Lean dès la phase de conception dans le cadre de l'Industrie 4.0.

2. Résumé

Lean est une approche qui vise à optimiser la performance globale d'un système de production en développant des méthodes d'amélioration permettant d'éliminer les gaspillages dans tout le processus industriel, de la conception à la distribution.

Des études sur Lean montrent que la prise en compte des fonctionnalités de Lean dans les phases de conception d'un nouveau système peut conduire à un système optimal dès la phase de conception, et ne nécessite pas l'application des outils de Lean qui sont parfois coûteux, chronophages, et gênants pour les utilisateurs en terme de sécurité de l'utilisateur. Ce qui pourrait conduire à des blocages difficiles à surmonter. En plus, la prise en compte des fonctionnalités Lean dès les premières phases de la conception du système de production pourrait faciliter le développement de l'Industrie 4.0.

Dans cette thèse, nous développons une approche innovante de la conception par l'intégration de Lean dès les phases de conception dans le but de choisir les solutions qui ne garantissent pas seulement une utilisation sûre du système, mais permettent de concevoir des systèmes (machines) fiables, sans gaspillage, rentables, etc.

Nous avons en premier lieu réalisé un sondage pour savoir comment les concepteurs intègrent les conditions d'utilisation dans le processus de conception de leurs systèmes, ensuite nous avons analysé la correspondance entre le Lean et l'Industrie 4.0 pour proposer une méthode qui va avec les occupations actuelles des industriels.

Pour cela, nous avons analysé les fonctionnalités de Lean, les identifié, et les classifié pour déterminer celles qui sont intégrables dans la conception de systèmes de production dans le contexte de l'industrie 4.0. Une démarche « Lean-Système-Design » a été développée. Elle définit un guide systématique et détaillé pour l'intégration de Lean dès les premières phases de conception.

Cette démarche est illustrée par deux exemples pédagogiques. Le premier porte sur le

cas de la conception d'un système intelligent de traitement des déchets. Le deuxième évoque le cas du débouchage de la buse d'une imprimante 3D. Une troisième application industrielle a été réalisée en partenariat avec une entreprise sur la conception d'un outil numérique de système de commerce de proximité.

Mots-clés : Lean, conception technique, conception interactive, méthodes de conception, conception inventive, Industrie 4.0, développement durable.

3. Structure de la thèse

L'objectif de cette thèse est d'offrir aux concepteurs une méthodologie et un outil de soutien qui peuvent être utiles pour concevoir un système performant dès la phase de conception initiale avec des besoins minimaux pour utiliser des outils de Lean dans sa phase d'utilisation.

Dans le chapitre 1, nous avons illustré l'introduction générale de notre recherche, qui comprend le laboratoire d'accueil, le contexte de la recherche, les problèmes de recherche et la contribution.

Nous avons positionné notre étude par rapport aux travaux réalisés dans le même domaine du Lean design, et nous avons analysé la littérature sur l'intégration du Lean dans les phases de conception.

La revue de la littérature du chapitre 2 vise à mettre en évidence les méthodes de conception utiles à l'intégration du Lean, et l'interdépendance entre Lean et « Industry 4.0 » (I4.0) pour comprendre l'homogénéité entre les deux concepts afin de faciliter leur intégration.

Pour cela, nous avons spécifié notre système complexe sur lequel notre méthodologie ciblée va réagir. Notre système est complexe, il peut s'agir d'un système de production, d'une machine et d'un système de service.

Ensuite, nous avons fourni les méthodes de conception existantes les plus connues, qui proposent des méthodologies pour augmenter les performances d'un système.

Ensuite, nous avons présenté une revue de la littérature sur l'intégration du Lean dans les phases de conception.

Pour cette raison, nous avons donné une introduction générale au concept de Lean, à son histoire, ses principes, ses méthodes et ses outils. Nous avons conclu que le Lean joue un rôle très crucial dans l'augmentation des performances d'un système non seulement dans la phase d'utilisation mais aussi dans la phase de conception, ce qui est à notre avis le choix le plus approprié.

Lean peut être utile pour intégrer les critères de performance requis pour améliorer l'efficacité des systèmes complexes en optimisant ses composants et ses interactions dès la phase de conception dans le contexte de l'I4.0.

Notre travail s'inscrit dans le cadre des tendances actuelles de l'I4.0, c'est pourquoi nous avons également présenté une introduction générale à l'I4.0 afin de souligner son importance sur les performances des systèmes.

Ensuite, nous avons étudié la convergence et la divergence des deux concepts Lean et I4.0. Nous avons noté que le Lean et l'I4.0 pouvaient se combiner pour concevoir un système de production optimal et moderne.

Au chapitre 3, nous avons développé une approche innovante pour intégrer le Lean dès les phases de conception afin d'avoir un système performant qui n'a pas besoin d'appliquer le Lean dans la phase d'utilisation pour améliorer ses performances.

Pour cela, nous avons élaboré une enquête pour montrer comment les concepteurs intègrent les conditions d'utilisation dans le processus de conception de leur système.

Ensuite, nous avons analysé la correspondance entre Lean et I4.0 pour proposer une méthode qui s'accorde avec les métiers actuels des industriels.

Et enfin, nous avons analysé les fonctionnalités du Lean, les avons identifiées et classées pour déterminer celles qui peuvent être intégrées dès la conception des systèmes de production dans le contexte de l'I4.0.

Pour prouver la faisabilité de l'approche, nous avons appliqué l'approche proposée Lean-System-Design du chapitre 4 à trois études de cas.

Le premier porte sur le cas de la conception d'un système intelligent de traitement des déchets. Le deuxième évoque le cas du débouchage de la buse d'une imprimante 3D. Une troisième application industrielle a été réalisée en partenariat avec une entreprise sur la conception d'un outil numérique de système de commerce de proximité.

En conséquence, pour mettre l'approche en pratique, nous avons commencé au chapitre 5 les premières étapes de mise en œuvre d'un module de logiciel de CAO pour soutenir l'intégration des fonctionnalités Lean dès la phase de conception.

Nous avons fourni les spécifications du logiciel pour permettre l'intégration des fonctionnalités Lean dès la phase de conception.

Nous avons présenté les spécifications et les diagrammes d'analyse UML : diagrammes d'objet, de cas d'utilisation, de classe, d'activité et de communication.

4. Introduction

Parmi les principes fondamentaux de l'Industrie 4.0, il convient d'associer les futurs utilisateurs, la direction de l'entreprise et la conception dans une réflexion structurée et approfondie afin de parvenir le plus rapidement possible à un modèle d'industrialisation qui permettra le meilleur compromis possible entre les exigences du marché, les contraintes de service et la performance industrielle (Fontanille, Charles, & Fr, 2010).

Selon Eiji Toyoda, il existe différentes possibilités d'améliorer le système de production (Dennis Pascal, 2016). Au fil des ans, des concepts et des méthodes sont développés pour améliorer les performances des systèmes de production (machines, processus).

Dans ce contexte, les entreprises ont tendance à s'appuyer sur des technologies récentes pour améliorer leurs performances en intégrant de nouvelles solutions de haute technologie. Cela leur permet de fabriquer plus rapidement des produits personnalisés, tout en réduisant les coûts, en éliminant le gaspillage et en améliorant les conditions de travail.

D'une part, ces systèmes peuvent être entièrement automatisés, et ainsi, certaines tâches humaines peuvent disparaître. D'autre part, le rôle de l'humain pourrait augmenter, et ces technologies peuvent les utiliser pour effectuer les tâches humaines de manière plus efficace et ergonomique.

Généralement, Ces systèmes causent des contraintes qui limitent leurs performances globales. Pour optimiser les performances de ces systèmes, les entreprises sont obligées d'appliquer les outils de Lean dans la phase d'utilisation de ces systèmes.

Lean est une approche qui vise à optimiser la performance globale d'un système de production en développant des méthodes d'amélioration afin d'éliminer les gaspillages de tout le processus industriel, de la conception à la distribution. Lean ne s'appuie pas seulement sur des méthodes qui couvrent les aspects organisationnels, mais aussi fournit des contraintes liées au comportement de l'homme vers un système utilisé.

Ainsi, Au fil du temps, le Lean est appliqué dans de nombreux autres domaines. Par exemple, le Lean IT dans le développement de développement des logiciels, le Lean Green pour augmenter les performances environnementales, etc.

Des études sur Lean montrent que la plupart des outils et méthodes techniques et organisationnels développés par les ingénieurs et les bureaux d'études ont pour but d'augmenter la performance globale d'un système existant en terme de productivité, de qualité, de délais et de coûts, etc.

D’autres études montrent que la prise en compte des fonctionnalités de Lean dès les phases de conception d’un nouveau système peut permettre d’obtenir un système performant dès la phase de conception qui ne nécessite pas l’application des outils de Lean qui sont parfois coûteux, chronophages, et gênants pour les utilisateurs en terme de sécurité de l’utilisateur, et aussi sa formation et son existence. Ce qui pourrait conduire à des blocages difficiles à surmonter.

L'intégration de Lean dès la phase de conception est une solution plus appropriée.

En effet, cela pourrait améliorer la performance globale du système et les conditions d’utilisation.

En plus, la prise en compte des fonctionnalités Lean dès les premières phases de la conception du système de production pourrait faciliter le développement d'Industrie 4.0.

Il convient de noter que de nombreuses études récentes affirment que la mise en œuvre des nouvelles technologies dans l'Industrie 4.0 est compatible avec les principes du Lean.

D’après la littérature, il y a des limitations dans les études qui évoque l’intégration le Lean sous forme des fonctionnalités. La plupart des méthodes existantes ne sont pas systématiques et restent dans la plupart du temps théoriques non détaillées, et non justifiables.

L’objectif de cette thèse est de développer une méthodologie innovatrice de la conception pour l’intégration de Lean dès la première phase de conception dans le but de choisir les solutions qui garantissent pas seulement une utilisation sûre du système, mais permet de concevoir des systèmes (machines) fiables, sans gaspillage, rentables, etc.

5. Contributions

Dans cette thèse, nous analysons dans quelle mesure le concepteur peut prendre les fonctionnalités de Lean dans la démarche de conception de systèmes de production dans le contexte de l’industrie 4.0.

Une démarche « Lean-Système-Design » a été développée. Elle définit un guide systématique et détaillé pour l’intégration de Lean dès la première phase de conception.

Notre cadre vise à améliorer la durabilité industrielle, l'agilité, la facilité d'utilisation, la flexibilité, le gain de temps, la rentabilité, la sécurité, etc., en proposant une méthode pour la conception d’un système ou une machine de production, dans le contexte de l'industrie 4.0 qui ne nécessite pas l'application de Lean dans la phase d'utilisation.

Dans ce contexte, de nombreuses questions peuvent être abordées :

Comment le concepteur prend-il en compte les exigences du Lean ?

Comment le concepteur prend-il en compte les informations et les conditions d'utilisation ?

Y a-t-il des convergences ou des contradictions entre les exigences du Lean et celles de l'Industrie 4.0 ?

Quelles fonctionnalités du Lean pourraient être intégrées dès les phases de la conception ?

Comment pouvons-nous aider les concepteurs à choisir des solutions qui n'arrête pas le système ?

Comment résoudre les contradictions, si elles existent, dues à l'intégration du Lean dans les phases de conception ?

Pour répondre à ces questions, les étapes du chapitre 3 sont organisées comme suit :

(1) Dans la section 1, nous présentons une enquête qui a pour but de déterminer comment les entreprises industrielles prennent en compte les conditions d'utilisation dès les premières phases de la conception.

(2) Dans la section 2, nous présentons une analyse des convergences et contradictions de la mise en œuvre des concepts Lean et Industrie 4.0 dans les systèmes de production.

(3) Dans la section 3, nous présentons notre approche systématique Lean-System-Design pour intégrer les fonctionnalités Lean dans chaque phase du processus de conception.

(1) Analyse des attentes des industriels pour l'intégration des tâches des utilisateurs dès la phase de conception

Pour comprendre comment les concepteurs industriels prennent en compte les informations et les conditions d'utilisation dans la phase de conception précoce, nous avons mené une enquête auprès de plus de 50 entreprises.

Nous avons analysé leur travail de conception et évalué s'ils ont besoin d'une nouvelle méthode structurée pour donner une image réelle afin de comprendre ce qui se passe dans les entreprises, ce qu'elles font, ce qu'elles utilisent et comment elles répondent à ce problème.

Notre objectif était de proposer une méthode qui non seulement prend en compte les facteurs humains et l'ergonomie dès la phase initiale de conception "HFE" proposée par (Xiaoguang Sun et al. 2018) qui est représentée dans l'enquête ; mais aussi, en considérant tous les autres critères de performance, liés aux systèmes de production et à la performance des machines, et à la capacité de l'utilisateur à utiliser un système qui doit être amélioré par l'application d'outils "Lean".

Plus de 50 experts du monde de la conception ont répondu à l'enquête. Ils représentent des entreprises en France, en Allemagne et au niveau international dans des différents secteurs d'activité tels que les machines et équipements, les matériaux industriels, les équipements et produits automobiles.

Voici une liste des 17 questions de l'enquête :

1. Dans votre travail de conception, y a-t-il des modifications (itérations) ?
2. À quelle(s) étape(s) les modifications de conception sont-elles fréquentes ?
3. Choisissez-la (les) raison(s) de vos modifications de conception.
4. Intégrez-vous actuellement des facteurs humains (HF) et des informations d'utilisation dans la phase de conception ?
5. Dans quelle(s) phase(s) intégrez-vous les informations d'utilisation ?
6. Actuellement, comment intégrez-vous les informations d'utilisation ?
7. Quelle(s) solution(s) choisissez-vous lorsque des modifications de conception sont nécessaires ?
8. Quelles sont les conséquences de l'introduction de systèmes de sécurité et de procédures supplémentaires ?
9. Pensez-vous être un "bon" utilisateur de votre produit ?
10. Normalement, à quel moment le manuel du produit doit-il être rédigé ?
11. D'une manière générale, qui doit rédiger le manuel du produit ?
12. Êtes-vous intéressé par une méthode qui vous permette d'éliminer ou de réduire les besoins des systèmes de sécurité ?
13. Souhaitez-vous présenter cette méthode proposée par Sun et al.2018 pour effectuer des travaux de conception ?
14. Souhaitez-vous collecter systématiquement les exigences et les informations relatives à l'utilisation ?
15. Souhaitez-vous compléter l'analyse fonctionnelle par une analyse des tâches ?
16. Seriez-vous prêt à définir l'entrée, la sortie, le contrôle, la durée et les ressources de soutien pour chaque tâche nécessaire à l'exécution d'une fonction ?
17. Seriez-vous prêt à coopérer avec nous pour tester la méthode proposée par Sun et al.2018 ?

Sur la base de l'analyse statistique des réponses, nous concluons que des modifications interviennent souvent à tous les stades du processus de conception, pour différentes raisons. Parmi ces raisons, le respect des normes et des lois ergonomiques et la satisfaction des exigences des clients sont les plus courantes.

L'intégration tardive des informations d'utilisation et le développement tardif du manuel d'utilisation peuvent également être à l'origine de ces modifications. Pour résoudre ce problème, les concepteurs mettent en œuvre certains systèmes de sécurité, ce qui peut diminuer la fiabilité du système. Et parfois, les concepteurs choisissent de concevoir un nouveau système, ce qui peut être très coûteux.

Nous concluons qu'il n'existe pas de méthodes systématiques dans le travail de conception pour intégrer le HFE. D'où l'importance d'une telle recherche.

Nous avons montré que la plupart des experts dans le domaine de la conception dans différents domaines de fabrication sont intéressés par une telle méthode qui, dès la phase de conception initiale :

- Intégrer les informations de l'utilisation dans la phase de conception.
- Optimiser l'interaction homme-machine.
- Réduire la nécessité d'appliquer le Lean et d'autres méthodes d'amélioration des performances dans la phase d'utilisation.
- Intégrer les principes du Lean dès la phase de conception afin d'améliorer les performances industrielles.
- Respecter l'environnement.
- Comprendre l'opérateur (Comportements, tâches, etc.) sur son lieu de travail pour l'aider à accomplir ses tâches de manière optimale dans un contexte industriel 4.0.
- Montrer concrètement le besoin du concepteur d'un outil utile pour mener à bien son travail de conception de manière optimale.

Jusqu'à présent, 22 entreprises souhaitent travailler avec nous.

Une entreprise a déjà collaboré avec nous.

Cela nous amène dans ce qui suit à analyser la convergence et la divergence entre ces deux concepts pour les intégrer dans les phases de conception.

(2) Convergence/contradiction entre le Lean et l'industrie 4.0

Nous avons analysé la littérature, ce qui nous a permis de constater que le Lean et l'Industrie 4.0 pouvaient se combiner pour concevoir un système de production optimal et moderne.

Selon cette analyse, I4.0 n'est pas en contradiction avec les principes du Lean en termes de satisfaction du client, de réduction des coûts et d'élimination des gaspillages pour concevoir un système de production performant.

Mais le risque que nous pensons qu'ils pourraient être tout à fait réels aujourd'hui est l'automatisation complète qui limite le rôle de l'homme, qui est l'un des éléments cruciaux de la philosophie Lean.

(3) L'approche Lean-Système-Design

Notre objectif est d'aider le concepteur à concevoir une machine ou un système qui n'a pas besoin d'appliquer les méthodes et outils Lean pour améliorer ses performances en phase d'utilisation.

Nous avons analysé les fonctionnalités du Lean et les exigences de l'industrie 4.0.

Nous avons constaté que :

- Certaines fonctionnalités techniques du Lean sont générales. Les concepteurs les prennent déjà dans la phase de spécification du processus de conception, sous la forme de critères tels que le budget, les normes, les spécifications techniques, etc.

- D'autres fonctionnalités non techniques, qui dépendent de tâches humaines telles que la sécurité, l'utilisation et l'ergonomie, sont surtout prises en compte dans les trois autres phases (phase conceptuelle, phase architecturale et phase détaillée).

Ensuite, nous avons identifié les étapes de notre étude :

(1) Identifier les critères qui dépendent du Lean et de l'I4.0.

(2) Classer les fonctionnalités Lean en fonction de la littérature et les avis des experts :

a. Les fonctionnalités qui peuvent être prises en compte dans les phases de conception. Ces fonctionnalités peuvent être classées en deux catégories :

- Fonctionnalités déjà prises en compte dans la phase de conception.

- Les fonctionnalités qui peuvent être prises en compte dans la phase de conception sur la base de notre jugement et de nos connaissances.

b. Fonctionnalités dont nous ne pensons pas qu'elles puissent être prises en compte lors de la phase de conception. Pour ces fonctionnalités, nous justifions les raisons pour lesquelles elles n'ont pas pu être prises en compte.

(3) Proposer une liste de critères qui pourraient aider les concepteurs à ne manquer aucune fonctionnalité (fonctionnalité technique et celles qui en résultent pour le Lean).

(4) Ensuite, dans l'étape suivante, pour aider le concepteur à vérifier s'il a pris en compte toutes les fonctionnalités, nous avons proposé une liste de contrôle d'évaluation basée sur tous les critères définis dans la phase des exigences (phase des spécifications).

Ces critères d'évaluation, en fonction des fonctionnalités Lean, peuvent être regroupés en types qualitatifs ou quantitatifs. Ici, la sélection des critères repose sur le choix du concepteur en fonction de son objectif comme le budget, la qualité, l'exigence technique, etc. Ainsi, il peut donner une pondération prioritaire à chaque critère.

(5) Dans cette étape, si l'ensemble de solutions devient nul en raison de l'intégration de fonctionnalités techniques et les fonctionnalités de Lean dans la phase de conception par le concepteur, nous proposons d'utiliser la méthode de conception inventive (IDM). Ainsi, pour trouver une solution innovante, nous combinons notre méthode avec la Méthode de Conception Inventive (IDM).

Cependant, malgré une utilisation de IDM, si le concepteur ne trouve pas des solutions basées sur tous les critères choisis, nous pensons qu'il doit abandonner certaines fonctionnalités Lean et continuer à répéter ces étapes jusqu'à ce qu'il trouve un ensemble de concepts de solution.

La démarche comporte 7 étapes illustrée dans le schéma ci-dessous.

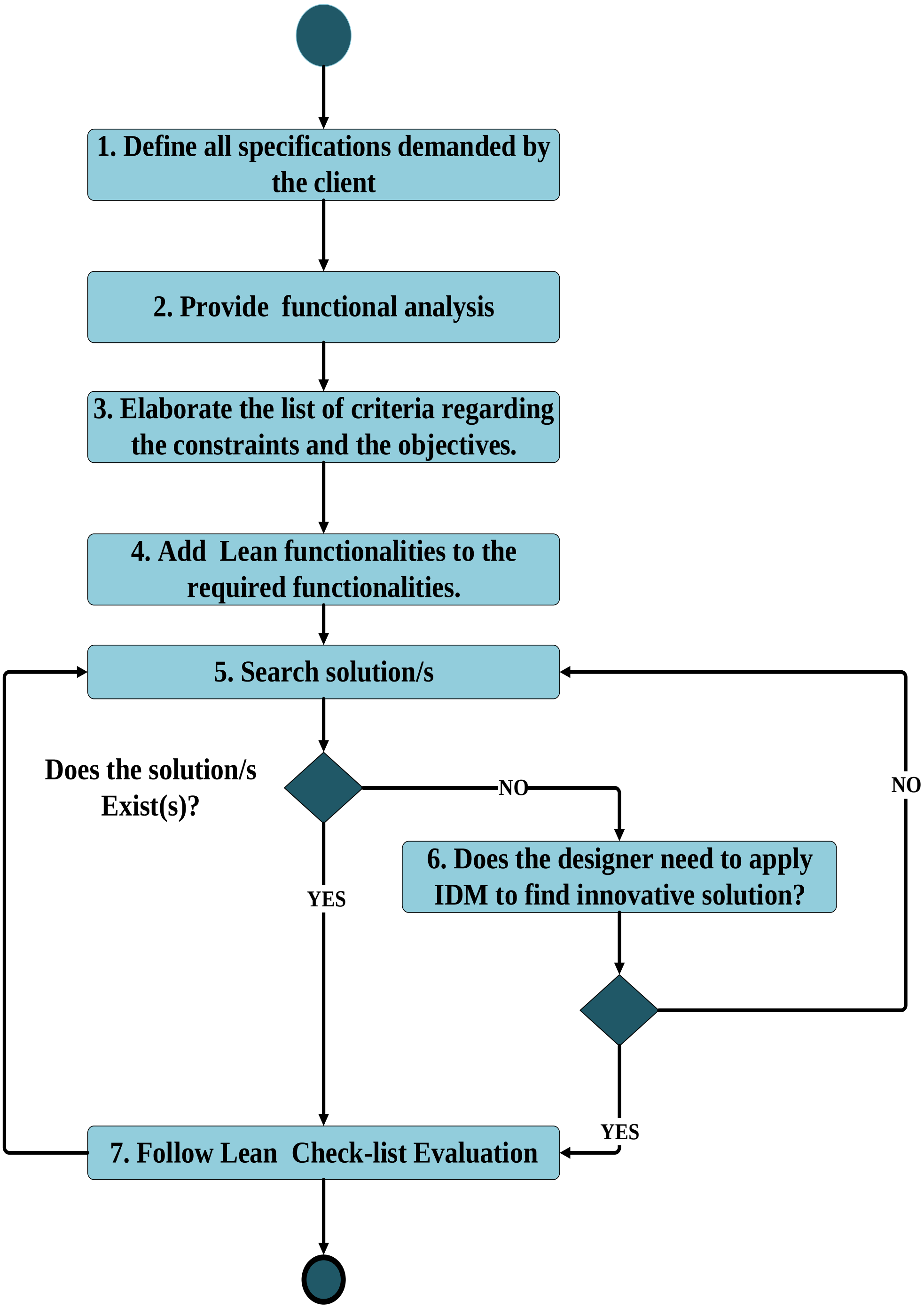

Figure 1 La démarche de l'intégration des fonctionnalités de Lean dès la conception

1. Dans l'étape 1, comme dans une méthode de conception classique, le concepteur définit toutes les spécifications demandées par le client.

2. Dans l'étape 2, le concepteur fournit une analyse fonctionnelle pour définir les fonctions techniques, les fonctions de service et les contraintes.

3. Dans l'étape 3, le concepteur élabore une liste de critères concernant les objectifs et les contraintes.

4. Dans l'étape 4, le concepteur ajoute aux fonctionnalités requises par les clients (fonctionnalités techniques) des fonctionnalités Lean, qui permettent de remplir les critères choisis dans l'étape 3.

5. Dans l'étape 5, le concepteur fait son travail pour développer une solution permettant de remplir toutes les fonctionnalités requises (fonctionnalités techniques et fonctionnalités Lean). Cependant, nous n'avons pas imposé ici la manière dont un concepteur doit procéder. Cette étape peut être différente selon le domaine et l'objet du processus de conception. Selon la situation et les conditions, le concepteur peut utiliser les méthodes et outils disponibles adéquats en sa possession (FAST, SADT, etc.) ou son expertise.

6. A l'étape 6, si le concepteur n'a pas trouvé de solution après avoir pris en compte toutes les fonctionnalités et contraintes qu'il souhaite, ce qui signifie que la zone de solution devient nulle.

Donc, pour résoudre le problème et trouver une solution innovante, nous proposons d'utiliser la méthode de conception innovante IDM qui est une extension de TRIZ pour la génération de concepts de solution en résolvant les contradictions.

Si malgré l'utilisation de l'IDM, le concepteur ne peut pas trouver de solution, il doit relâcher certaines contraintes en enlevant certaines fonctionnalités allégées ou d'autres contraintes (coût, etc.).

7. Dans l'étape 7, le concepteur suit la check-list d'évaluation Lean avant le prototypage afin d'éviter tout manque.

6. Spécifications du logiciel Lean-System-Design

Dans cette partie, nous proposons les spécifications du logiciel en fonction des critères et des fonctionnalités proposées. Nous présentons successivement les spécifications des modules, l'architecture des modules, puis les diagrammes d'analyse UML : objet, classe et activité.

Nous décidons de mettre en œuvre l'approche Lean-System-Design pour l'intégrer sous forme de module dans un logiciel de CAO "Lean-System-Design (LSD)".

Notre logiciel LSD consiste à intégrer les fonctionnalités Lean pour réaliser les spécifications fonctionnelles afin d'aider les concepteurs à prendre en compte le maximum des critères de performance pour satisfaire toutes les exigences fonctionnelles, d'utilisation et de performance.

Pour cela, les données de la liste des critères, les fonctionnalités Lean appropriées et les paramètres Lean doivent être fournis au concepteur, en plus des méthodes de conception (FAST, IDM, Décomposition des tâches, etc.) pour réaliser les spécifications fonctionnelles initiales, conceptuelles et détaillées.

L'architecture de la modélisation visée dans notre méthodologie se compose de quatre parties (figure 2) :

1. Dans la liste des exigences, le concepteur recueille toutes les spécifications du système.

2. Le centre de conception couvre les fonctions et les tâches.

3. Dans le centre Lean, le concepteur utilise la liste des critères adaptés aux exigences, accompagnée des fonctionnalités et paramètres Lean appropriés.

Grâce à ce centre Lean, le concepteur peut optimiser toutes les solutions, des tâches techniques et sociotechniques, aux tâches internes et externes.

4. Dans le centre IDM, le concepteur peut utiliser l'IDM pour trouver des solutions plus adaptées aux critères choisis et au Lean si l'ensemble des solutions est nul.

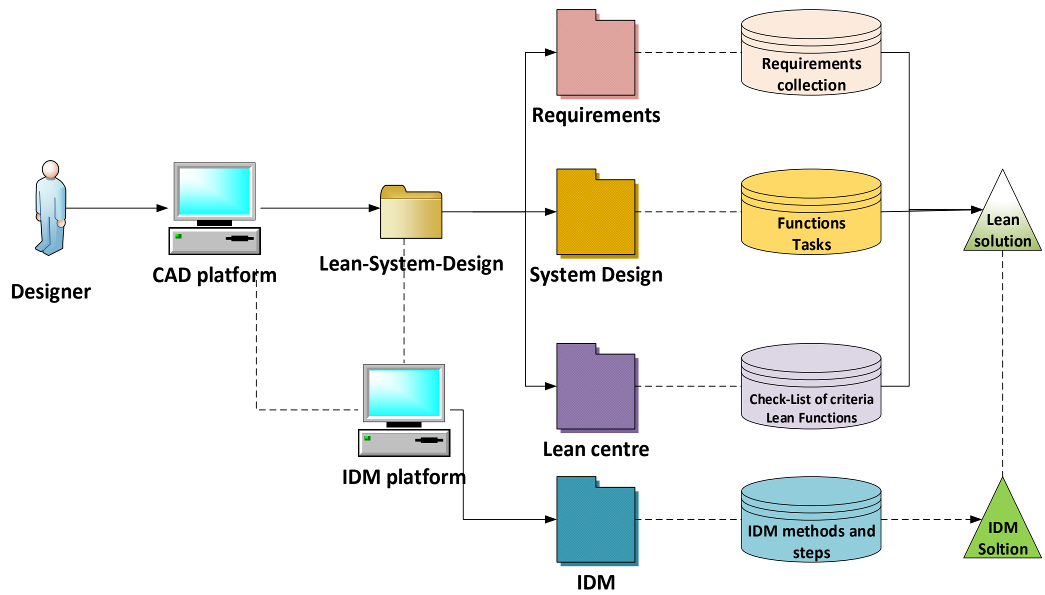

Figure 2 L'architecture de notre modèle LSD

Nous avons montré les premières étapes de la mise en œuvre du Lean-System-Design dans les logiciels de CAO.

Le cas d'utilisation, la classe et les diagrammes d'activités du module Lean-System-Design ont été dessinés par UML.

Nous avons également assuré la communication pour le module.

Malheureusement, les modèles UML ne sont pas encore convertis en modules CAO par programmation. Ce sera notre futur travail. Nous préférons de supprimer toutes les limitations liées à notre approche pour réduire la charge de travail du concepteur avant de passer à la partie développement informatique du module LSD.

7. Conclusions

La méthode de conception proposée présente certaines limites, qui peuvent être améliorées afin de faciliter son utilisation par le concepteur.

Ces limitations ont été conclues à partir de l'expérience des utilisateurs lorsque nous avons appliqué notre approche aux deux exemples présentés au chapitre 4 sur la machine de traitement des déchets et le système de service.

La première limitation est que notre approche ajoute des fonctionnalités de Lean aux fonctionnalités techniques requises par le client. Ce qui augmente donc la charge de travail du concepteur. Pour l'instant, nous n'avons pas évalué les séquences d'une nouvelle charge de travail sur la productivité et la motivation du concepteur.

La deuxième limitation peut être que le concepteur, selon ses connaissances, ne sait pas comment choisir les fonctionnalités Lean adéquates pour son problème.

Les fonctionnalités Lean ne fournissent pas au concepteur les solutions les plus performantes. La génération du concept de solution dépend des méthodes, des outils, des connaissances et des compétences du concepteur.

La troisième limitation est que certains liens disponibles entre les fonctionnalités Lean et les paramètres Lean ne sont pas fournis, et entre les fonctionnalités quantitatives et qualitatives. Le concepteur peut avoir quelques difficultés à établir ce lien.

La quatrième limitation est que l'IDM n'est toujours pas prêt à résoudre une contradiction de service pour un système de service.

Malgré les applications présentées au chapitre 4, l'efficacité du notre approche ne peut être suffisamment garantie sans le développement complet du module ou du logiciel et son application à un système de production complexe.

Afin de minimiser les limites de la méthode proposée, des recherches futures seront adoptées pour améliorer de plus en plus notre approche proposée.

Pour lever l'ambiguïté, nous classerons les fonctionnalités Lean en lignes directrices de conception quantitatives et qualitatives qui facilitent l'utilisation du module LSD par le concepteur.

Nous améliorons la check-list à classer pour chaque agent et interaction du système.

Nous poursuivons le développement du module CAO dans un premier temps, et du logiciel afin d'être prêt à être appliqué à un cas industriel complexe.

Nous développons le concept de génération de solutions pour les fonctionnalités Lean pendant la phase de conception.