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A Systematic Improvement Model to Optimize Production Systems within Industry 4.0 Environments: A Simulation Case Study

Marcel Groten [1] and Sergio Gallego-García [2,*]

[1] Project Portfolio and Production Management, Bayer AG, Pharmaceuticals, 51373 Leverkusen, Germany; Marcel.Groten@hotmail.de
[2] Industrial Engineering Technologies of the International School of Doctorate, National Distance Education University (UNED), 28040 Madrid, Spain
* Correspondence: sgallego118@alumno.uned.es; Tel.: +34-682-880-591

Featured Application: Facilitate the optimization of relevant KPIs to increase the long-term sustainability of manufacturing organizations as a result of a novel systematic improvement model that will enable integration with Industry 4.0 technologies.

Abstract: The industrial revolutions and their impact on production systems have increased productivity and quality in manufacturing over time. Lean methods have been the driver of the development of production systems from the 1990s to the rise of the fourth industrial revolution, or Industry 4.0. However, many different approaches and methodologies have been described, applied, and discussed for achieving improvements in production systems. As a result, organizations are often confused in regard to the order, the convenience, and the outcomes intended by the different improvement strategies and techniques. This paper provides a systematic sequence of process optimization steps that can be applied to any organization. A conceptual model was built based on the systematic sequence. In addition, a simulation model was built with the goal of representing and quantifying the sequential steps of the conceptual model. The results of the simulation model show a clear improvement in quality, performance, and economic indicators, with the first two steps in the optimization sequence providing critical initial information, while the three last steps served as net contributors to a global production system improvement for demanding market scenarios. Finally, we analyzed the impacts of Industry 4.0 on production systems and developed a methodological sequence to design, select, implement, and control projects, even those that include Industry 4.0 technologies.

Keywords: production management; lean management; Industry 4.0; project management; process improvement strategies; business transformation; production system; organizational capabilities; continuous improvement

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1. Introduction

Since the first industrial revolution, each revolution has resulted in manufacturing advances [1], and the development of the manufacturing industry has profoundly impacted economic and societal progress [2]. The human society has sought progressive improvements in life quality, which has, in large part, inspired these industrial revolutions [3]. For this purpose, there have been manufacturing efforts in research, development, production, and management of complex industrial processes by using the innovative production technologies available at the time [2].

Today's businesses are increasingly competing on time and quality [4]. Global competition is becoming more and more intense, and the market, besides demanding higher quality, greater product variety, and lower cost, is also demanding the delivery of products in shorter delivery lead times [5,6]. These conditions apply pressure on manufacturers to maximize the efficiency of their operations and on manufacturing to meet customers' requirements. In order to achieve this goal, a wide range of methodologies are available, including lean manufacturing (LM), six sigma (SS), the theory of constraints (TOC), quick response manufacturing (QRM), and agile manufacturing (AM), which appear to be amongst the most popular methods across the academic literature [6–8].

Many separate philosophies have evolved to achieve competitive goals. Lean production provides operational efficiency and benefits to manufacturing businesses. In addition, the principles of lean production can be applied in every industry across the globe [9]. For example, the elimination of all forms of waste as well as teamwork and learning organization, the practice of continuous improvement, single-minute exchange of die (SMED), visual control, and 5S (Seiri, Seiton, Seiso, Seiketsu, and Shitsuke) are important and applicable to all organizations [8]. The issue has been that the literature advocates "full" adoption of lean production principles, whereas empirical evidence indicates partial adoption to be more effective [10]. Many research studies have analyzed the combination of two improvement strategies such as the simultaneous integration of lean and agile paradigms [11]; for example, the integration of six sigma and TOC for continuous improvement or the integration of TOC with lean manufacturing [8] or lean and six sigma called lean six sigma [12–14]. Moreover, lean and agile manufacturing have been analyzed in the literature in progression, in combination, and in isolation [15]. In addition, there are complementary elements in both lean and QRM that have been analyzed in previous research [7,16].

Lean production systems have been established in almost all industries and have become an industry standard with the publication of the guidelines and standards in VDI 2870 in 2013. The model described in the VDI 2870 represents a four-phase model: design, implementation, transition, and operation [17]. In this regard, it is focused on the goals of lean, and it is a design-driven approach without application of the learning process that could be exploited with artificial intelligence and machine learning algorithms. Moreover, most companies are already established, and, therefore, the improvement of business processes must be implemented based on the current state that should be first analyzed while maintaining system operations. Afterwards, despite lean production being the most widely applied system, other improvement strategies provide other benefits and trade-offs that should be considered when choosing the appropriate methods and systems to be applied. In addition, the development of specific tools was not provided in this standard, even though it offered a list of methods [17].

Regarding the line of research on implementation cases and results, it should be stated that this is still at a very early stage of understanding [18]. The companies have to analyze, monitor, and make improvements for their existing manufacturing systems to comply with the market competition. Different companies use different methodologies, approaches, and tools for implementing programs for continuous quality improvement. Moreover, each company must use a selection process and a combination of different approaches, tools, and techniques that they can customize for their implementation [19].

As described before, manufacturing management literature has shared many paradigms with the aim of helping companies to address the challenges of maintaining competitiveness in the global market. The various continuous-improvement manufacturing models provide manufacturing systems with certain capabilities such as customization, flexibility, inventory reduction, lead time optimization, quality, responsibility, etc. [20]. For instance, one of the benefits of using AM is its robustness, while for LM, the focus is identification and simplification [15]. However, none of them is able to provide all of the desired features [20], so, for that reason, developing a systematic approach concerned with how to cover all necessary features, including the ways in which these systems complement each other, is sorely needed.

An integration model such as the one presented in this paper would provide a platform for different continuous-improvement strategies to interact and work together. This research can help managers understand that these various continuous-improvement approaches are not mutually exclusive. Our case study results showed the importance of the systematic-improvement model. As a result, there have been many theoretical and practical models presenting optimization strategies as stand-alone analyses and cases studies or as a combination of two systems, such as lean and six sigma, lean and agile, or six sigma and TOC, among others. However, there has been no guidance for which strategic project steps should be implemented for a production system to reach its best potential with a systematic business improvement model, which would enable said business to secure its position in the market. This absence led to the research challenge that is the focus of this paper: the integration of relevant improvement strategies and techniques in one methodological model that could be customized for most manufacturing systems. In this regard, the paper does not integrate all strategies and techniques; instead, it suggests a selection based on scientific soundness and recognition for their complementary principles for integration, as this has not been addressed in the literature.

In this context, several models have been developed to improve the performance and sustainability of operations within manufacturing organizations. The goals of these models were always to increase effectiveness and efficiency while maximizing customer service levels while maintaining the lowest possible costs. Recently, lean and other improvement strategies have been used for many different purposes and challenged researchers and practitioners to identify the appropriate sequence and timing for when and how to apply them. In this regard, there has been little guidance in the sequences to be followed or considered when designing and assessing the impacts of optimization projects. Methods, techniques, and their study are key for successful planning and control as well as for the optimization of target indicators. Thus, the aim of this research was to propose an integral sequence model for manufacturing organizations to improve their sustainability production system long term as well as to identify the impact of different sequence steps on target indicators. Current manufacturing has not yet achieved a level on par with Industry 4.0 expectations despite the many researchers and companies working to bring it to fruition [21]. However, there is still a long way to go [22]. Therefore, this paper discusses a methodological model that may provide guidance for the successful design and execution of integrated improvement strategies and Industry 4.0 optimization.

Our research provided a novel improvement model that consisted of several sequential steps for applying various improvement strategies and methodologies so that managers may choose the most suitable strategy for their purposes. Furthermore, we developed six different simulation models for the different steps in the improvement sequence with the goal of quantifying the optimization impacts of each stage. This analysis was performed for two different demand scenarios and for a defined set of indicators. Finally, Section 6 of this paper describes the impact of Industry 4.0 on production systems and their optimization processes as well as defining the methodological framework for the integration of improvement strategies and Industry 4.0 technologies to secure the long-term viability of a manufacturing organization.

2. Methodology, Fundamentals, and Materials

2.1. Methodology

In this study, the methodological approach was as follows:

1. Literature research on:
   (a) Evolution of industrial revolutions and production systems.
   (b) LM and strategies for improvement.
   (c) Challenges of LM and strategies for improvement.
2. The development of a conceptual model describing a systematic sequence for optimization. It was designed as a framework for informed decision making when selecting the appropriate strategies, concepts, techniques, and steps for the improvement of organizational processes.

3. The design of simulation models and the assessment of the different stages and their improvements along the optimization sequence, as described in the conceptual model. In addition, the models simulated the potential impacts of the main steps.
4. A discussion of results in regard to the potential projects that may be selected as well as the project management required for business improvement strategies and Industry 4.0 outcomes.
5. A critical reflection of the research performed as well as suggestions for potential future research based on the research and results of this paper.

The authors considered any company that was considering an improvement and transformation process, already had such an implementation in progress, or had already implemented improvement methodologies, and, therefore, designed the framework around these different scenarios to evaluate and predict the benefits and challenges associated with the different stages.

2.2. Industrial Revolutions and Production Systems

The first industrial revolution has usually been described by its mechanization of manufacturing [23], while the second has been credited with the introduction of mass production [24]. The third industrial revolution began in the early 1970s [24] and has been defined by its induction of advanced electronics and information technologies for the automation of production processes [1,2,24]. In 2011, the initiative "Industry 4.0" was introduced by representatives of business, politics, and academia [25]. It is based on the establishment of smart factories, smart products, and smart services that would utilize the Internet of Things and artificial intelligence [26], with the goal of improving the resilience and competitiveness of manufacturing companies [27].

Any production system includes inbound and outbound logistics as well as operations and their related support activities. Production is the foundation of human activity. Natural resources have been transformed into useful products through production processes to meet the needs of society [28]. A production system is characterized by the process of transforming materials into finished products and includes the related responsibilities of production planning and production control [29]. The current understanding of production management varies widely from an authoritarian point of view of planning and production control to a global understanding of production management as the management, the design, and the development of an entire manufacturing company [30]. Production management includes the tasks of designing, planning, monitoring, and controlling the productive system and business resources such as people, machines, material, and information [31]. The automobile industry had already changed the principles of production, namely, after World War I, where the production system evolved from craft production to mass production. As a result, the United States led the world economy. Then, a second change took place after World War II when Eiji Toyoda and Taiichi Ohno pioneered the concept of lean production [9].

2.3. Lean Production System and Improvement Strategies

Lean is a process improvement methodology used to deliver products and services better, faster, and at lower cost [12]. Lean manufacturing is based on the principles and processes of the Toyota production system (TPS) [32]. The TPS developed as a result of the market requiring the production of small quantities of many varieties under low demand conditions after World War II to test whether Japanese car manufacturers could compete with the mass production systems established in Europe and the United States [33]. Toyota produced automobiles with less inventory, human effort, investment, and defects and introduced a greater variety of products [34]. Lean manufacturing creates more value for customers by eliminating activities that do not add value to the product or service. Lean production can be considered as a philosophy and a set of tools and practices for the continuous improvement of production operations that are of the highest quality, the lowest cost, and the shortest lead time [32]. Personnel has a fundamental role in the process of developing a lean strategy and can be essential for the success of lean techniques, as the early adopters in Japan discovered [35].

Lean production is one of the best approaches for promoting business excellence through continuous improvement [36], and lean management remains the most popular approaches to operational excellence across industries. The lean approach has evolved over time and been embraced by other industries and in other cultures [37].

The standard elements of a global production system are quality management and robust processes, logistics and production control, work organization, employee orientation, standardization and visual management, continuous improvement, and product and process development. Various other strategies have emerged in the literature to cope with changing market requirements and to optimize production systems:

- Lean manufacturing places two management goals above any other: continuous improvement and the constant need for waste reduction [16] to reduce costs [6]. LM seeks to continuously decrease costs, defects, and inventories while increasing product variety [38]. The principles of LM eliminate waste in every function within a company; although, at the very beginning, it had been focused on production [6]. To achieve this goal, Toyota applied the scientific method to all levels of the workforce, ensuring that people shared a common goal and vision of what the production system should be [39]. Without using lean methods and improving processes, the processes could become unstable. Stability is defined as the capability to produce consistent results over time. Instability is the result of process variability. The first step in creating lean processes is to achieve a basic level of process stability that can be consistently maintained [40].
- Six sigma is a management philosophy developed by Motorola in 1986 that requires setting extremely high objectives, collecting data, and analyzing results to reduce defects in products and services. Today, it is used in many industrial sectors. It has also been referred to as a systematic approach to the quality improvement of process outputs with variability minimization in manufacturing and business processes [15]. Six sigma helps to manage the challenge of complexities in products and processes by minimizing the risk of low quality by controlling variability. After inception of TQM in the early 1980s, six sigma arrived as an element of TQM that was seen an evolution in quality management [19]. Six sigma is a systematic methodology aimed at operational excellence through continuous process improvements that have been successfully implemented worldwide for over 20 years, producing significant improvements to the profitability of many large and small organizations [41]. Six sigma has been called the best-known approach to process improvement. It was initially introduced in manufacturing processes; today, it is applied in all areas of organizations [41].
- The origins of TOC date back to the late 1970s when Eli Goldratt helped to develop a scheduling program that increased a plant's output through optimized production technology (OPT), and it was officially introduced in the U.S. in 1980. The theory of constraints involves a continuous-improvement approach that identifies, exploits, and manages the constraints on a system to increase its throughput [42]. TOC can respond to an increasing number of variants in the production processes that can bottleneck resources. By identifying a constraint or bottleneck in a system that affects the throughput, TOC converts into a "pacemaker" [8]. According to Goldratt, while dealing with constraints, managers are required to make three decisions. These are [4]:
    - Decide what to change by identifying core problems;
    - Decide what to change to develop simple, practical solutions;
    - Decide how to cause the change by implementing solutions.
- Quick response manufacturing (QRM) was introduced in 1998 by Suri, and it was derived from the concept of time-based competition (TBC) [8]. QRM answers the challenge of low-volume–high-variety production systems, which required a different approach to process improvement and performance [7]. It reduces the lead time of

the provided products to satisfy customers and respond rapidly to the actual demand, which is why it is often used in dynamic production with high variety and customization. However, it is a company-wide strategy that strives to reduce lead times in all operations across the whole organization, leading to improved quality, reduced costs, and quick response [8]. The QRM approach uses a mathematical foundation that explores the concepts of queuing theory and systems dynamics [16]. QRM principles reduces lead time using a step-by-step methodology, manufacturing techniques, as well as analysis methods and tools that take into consideration fundamental principles of system and manufacturing dynamics [6].

- The concept of agile manufacturing was proposed in 1991 at the end of a government-sponsored research effort at Lehigh University. Being “agile” refers to the capability to manage change and uncertainty as well as to integrate a business’ employees and information tools in all aspects of production. For businesses, agility translates into cooperation that enhances competitiveness. An agile partnership crosses company borders and works together [43]. Agile manufacturing is an approach for remaining competitive in a global business world by using market knowledge and virtual corporations to exploit profitable opportunities in a dynamic marketplace [15]. While agile manufacturing is responsive to survive in continuously and unpredictably changing environments, it focuses on a fast response throughout the supply chain to mitigate the effects of variability [8].

2.4. Materials

The following sources, methods, and tools were used to perform the research:

- Books, conferences, and articles: a selection of books, conference proceedings, and articles were procured by searching using keywords for improvement strategies, business and process improvement, lean manufacturing, six sigma, lean sigma, theory of constrains, quick response manufacturing, agile manufacturing as well as combinations of the terms, such as “lean manufacturing” and “six sigma” in order to discover existing research methodologies and use cases for their combination.
- System dynamics: system dynamics (SD) is a computer-guided approach for studying, managing, and solving complex feedback problems with a focus on policy analysis and design [44]. It is a methodology for the simulation of dynamic models by studying the characteristics of the information feedback of industrial systems. SD has been applied to various systems from corporate strategy to the dynamics of diabetes, and it can be applied to any dynamic system with any time and spatial scale [45]. In an organizational context, SD assists in determining which policies should be used based on the organizational system results over time [46]. It was the perfect methodological tool to validate and quantify the steps of the systematic improvement model.
- Vensim: Simulation is the only practical way to test models [45], and for this reason, simulation was used to reproduce our model. In the market, there are different software packages and languages that enable system dynamics modeling, such as AnyLogic, Dynamo, iThink, Powersim, Stella, and Vensim [47]. VENSIM simulation software was selected for this research work. Vensim is a registered trademark of Ventana Systems Inc. (Harvard, MA, USA) and serves as a platform to build stock and flow model diagrams as well as causal loop diagrams.

3. Conceptual Development for Systematic Improvement Model

The vision was to provide a conceptual model that would provide the optimal optimization steps that could be applied successfully across organizations and industries. Therefore, it could assist management at all levels in the determination of what timelines, methods, and technologies to implement based on the model and on the characteristics of the company and its goals. The conceptual model would serve as a basis for decision making on future improvement projects based on their modeled ability to improve service for end-customers, reduce operational costs, and secure long-term viability and competitiveness for the organization.

3.1. Characterization of Improvement Strategies

There are many different concepts, methods, and tools that can be used to maintain quality and assist in continuous development and optimization in a company [48]. After more than 50 years of use in production systems, Toyota has developed a range of methodologies and tools that have been tested around the world by companies of all sizes and sectors, obtaining dramatic improvements in all their processes and equally significant reductions in production costs [34]. In addition to the main LM principles, there have been other improvement strategies that may complement the improvement sequence. The first step is to characterize the improvement strategies according to the same criteria, which can be seen in Table 1.

Table 1. Characterization of improvement strategies: principles, tools, factors, and target KPIs (own elaboration based on [4–7,9,11,15,16,19,20,37,41,43,48–55]).

No.	Improvement Strategy	Characterization Criteria			
		Principles	Tools	Factors	Target KPIs
1	Lean Manufacturing (LM)	Value, value streams, continuous flow, pull, and perfection	Kaizen, cellular manufacturing, just-in-time (JIT), one-piece flow, Kanban, total productive maintenance (TPM), 5S, visual management, value stream mapping, SMED, Jidoka, Poka-Yoke, among others	7 zeros: zero defects, inventory, accidents, delays, breakdowns, changeovers or setup times, and waste	Cost reduction, fewer resources, less human effort, and lower inventory
2	Six Sigma (SS)	Concentration on the customer, customers' specifications, real data and facts, continuous improvement, proactive management, and cooperation	Define–measure–analysis–improve–control (DMAIC), statistical analysis, regression analysis, hypothesis testing, design of experiments, Taguchi methods, among others	Rejection rate, defect rate, delays in products, processes and transactions, process capability indices, and process yield and loss	Improve quality, reducing process deviations and defects, and process performance
3	Theory of Constraints (TOC)	The five steps of on-going improvement. Identify constraints for exploiting and elevating it to improve overall output, thinking process	Five steps, types of constraints, three questions of the thinking process, drum–buffer–rope scheduling, buffer management, among others	Capacity utilization, throughput time, variation, quality, and demand	Throughput, inventory, operating expenses, net profit, ROI, and cash flow
4	Quick Response Manufacturing (QRM)	Ten principles and four core concepts: power of time, organizational structure, exploiting system dynamics, and reduction in lead times globally	Time-based competition, manufacturing critical path time map, the QRM cell, multi-skilled cross-trained teams, market target sub-segments, paired-cell overlapping loops (POLCA), utilization under 80%, rapid modelling tools and system dynamics, among others	Quick design Quick manufacturing Lead times of all tasks Speed response	Lead time reduction, quality, product variety, costs, delivery times, and product introductions
5	Agile Manufacturing (AM)	Value to customer, ready for change, valuing human knowledge and skills, and virtual partnerships	Virtual enterprise, concurrent engineering, physically distributed teams, rapid partnerships, product–process integration, rapid prototyping, e-commerce, among others	Internal: technologies, staff, educated management, and information External: speed, flexibility, responsiveness, etc.	Adaptability, service, quality, cost, and lead time

3.2. Optimization Sequence Steps

While acknowledging that the best selection of strategies to increase customer responsiveness will depend on the product, production system type, and its market segment, this research proposed a sequence of steps for the optimization of an organization. Its goal was a general standard that could serve as a reference for those developing optimization plans for an organization. However, that did not mean that every step or every method or technique could be applied for any sector, any production, or any product. However, certain lean principles such as continuous improvement, waste reduction, visual management, 5S, etc., could be readily implemented in most manufacturing environments [8].

We suggested that full or partial and iterative implementation of the improvement strategies could generate progressive changes that an organization would make in response to external pressures to improve operational performance for securing their viability in the long term. First, for initiating the improvement process, Figure 1 provides the general methodological steps:

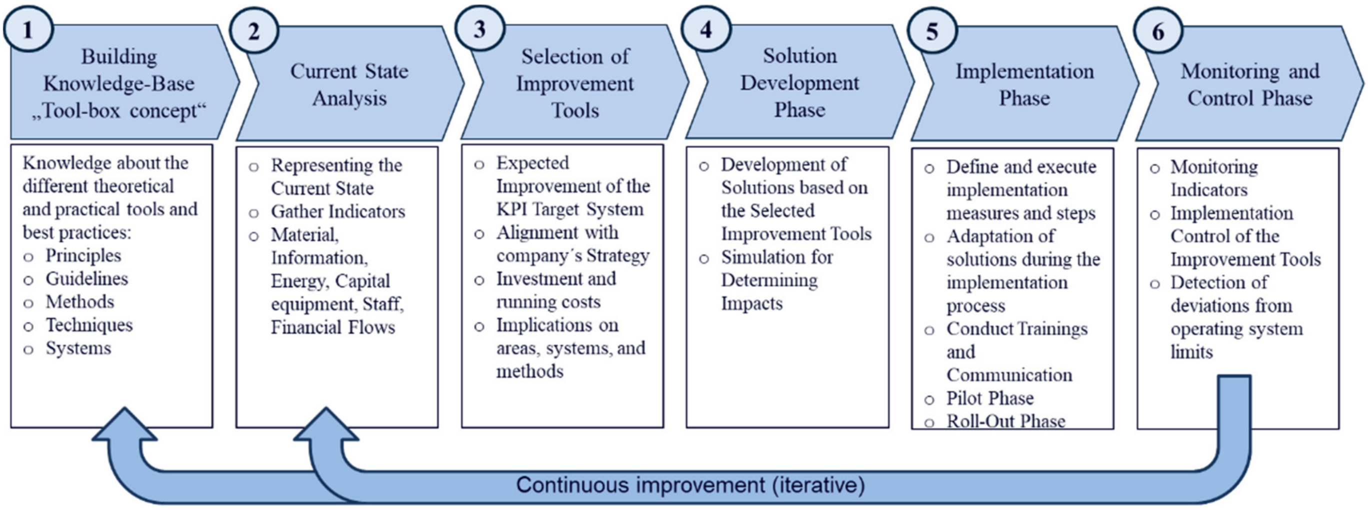

Figure 1. Methodological steps for systematic process optimization (own elaboration).

The development of a conceptual model describing a systematic sequence of optimization for reaching the best possible state of an organization would serve as a framework. Within the conceptual model, the third step referred to the selection of improvement tools or strategies that should be applied when pursuing a certain goal. This step was analyzed in detail with support, as shown in Figure 2. When defining the optimization steps for an organization, the following questions had to be answered:

1. What are the means that can be used for improvement?
2. What is the current organizational status?

The first question provided the knowledge and tools that could generate improvement. This knowledge base consisted of theoretical formulations and practical experiences and required continuous development to enable the organization to have more capabilities to face any challenge and optimization goal. For building a knowledge base, it is key to investigate the existing principles, guidelines, methods, techniques, and systems as well as best practices from case studies that can provide a "full-package toolbox" for use when responding to organizational and environmental challenges and their associated risks. The "toolbox" concept refers to the accumulated experiences and knowledge gleaned from literature, benchmarks, organizational experiences, and case studies that develop skills that can be applied when they are needed, thus providing the right "tool" at the right moment.

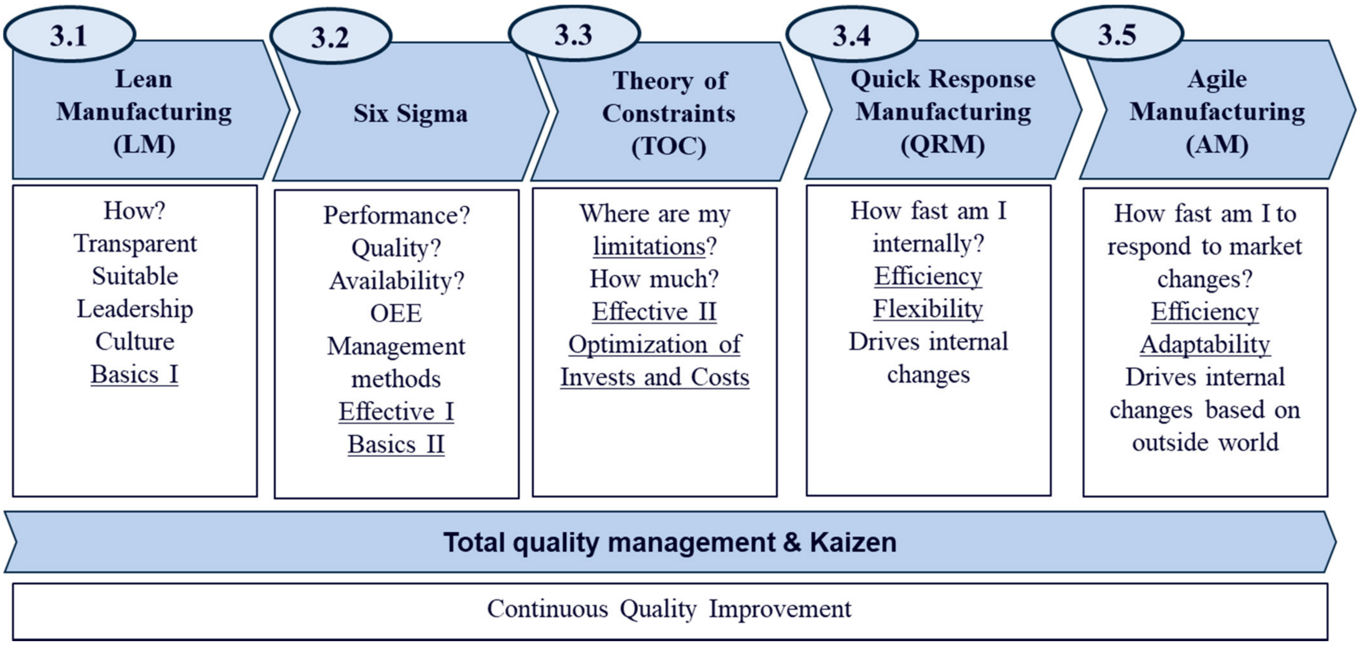

Figure 2. Systematic improvement model: selection of improvement tools (own elaboration).

The second question sought details about the current state of an organization and its manufacturing systems, as these were fundamental to identify where and what needed to be improved. This second step required interviews with personnel from management to operational levels so that the management and technical processes could be mapped. It provided information on the different needs and workflows in the organization as well as data that could be analyzed to provide a realistic view of the organizational status based on selected indicators.

Based on the first two steps, data regarding the organization and its current resources, capabilities, etc., were gathered. This information would guide the selection of an improvement project based on the priorities and needs of the organization as well as its potential.

The sequence was built with the following interactions: LM provided transparency and optimization of processes. Then, once the process was defined, variability could be measured. Once variability was measured, six sigma principles would be used to define the boundaries for consistent production, including performance, quality, and availability. Next, constraints could be identified based on TOC principles using current capabilities and quantities to determine whether the predicted targets could be reached or if an expansion of system constraints are required to balance the production system. However, since traditional methods for expansion can involve significant investments of effort and resources, the LM and SS principles were applied to adapt existing processes and reduce improvement costs. After the TOC was considered, the QRM was applied to reduce the lead times of all internal processes and, therefore, increase efficiency in responding to customer demands. Then, AM assisted the organization in developing strategies to increase their ability to adapt to all potential scenarios.

The optimization sequence in step three, as can be seen in Figure 2, was based on the various improvement strategies that have been developed over time. They were informed by the answers to the following questions:

3.1. How does the organization perform its processes?

3.2. How can the effectiveness of the organization terms of availability, quality, and performance of all processes be measured and improved?

LM was applied to the answer for the first question as it provided order and transparency with 5S and value-stream mapping (VSM) as well as improved relevant indicators with SMED, Kanban, or with a pull production system. Moreover, it provided the required transformation within the organization, such as increasing coordination between teams and continuous mindset improvement for employees along with LM and lean leadership strategies applied across the production system and organization. This step was the foundation for any later changes, named "Basics I", as it introduced the LM concept in the organizational structure as well as the management and technical processes.

SS was applied to the answer to question 3.2. Since management and technical processes had been classified as coherent, clean, and transparent as well as improved with question 3.1, this step measured the performance, availability, and quality of the production system to increase the stability and quality of manufacturing processes with statistical process control (SPC) and to improve the availability and performance of equipment with total productive maintenance (TPM). This step represented the second fundamental step, "Basics II", as without controlling the process and its availability and performance, the manufacturing organization would not be able to meet market demands, and, therefore, it would be not effective. The SS step converted the production system into an effective system that could supply the required quantity with the required quality.

Once the basics for an effective system were built with the first two steps, the analysis of the constraints and barriers in the production system could be evaluated. The data for this step were informed by the answers to the following question:

3.3. Where are the organization limitations? When does the bottleneck occur? How often does each type of bottleneck happen? How much impact does the bottleneck have?

The TOC addressed this issue by improving productivity and performance based on the production system limitations and its characteristics (frequency and impact) and, then, based on that conclusion, indicated whether reducing the limitations or merely adapting to them was a better choice for optimization.

The fourth and fifth steps referred to the efficiency of the system in terms of process performance speed. The first question focused on the internal response capability of the production system to market demand, and the second addressed the response capability in terms of market demand changes. The questions related to these steps were:

3.4. How fast does the production system internally respond to market demands?

3.5. How fast does the production system identify and respond to market changes?

Question 3.4 was based on QRM push-oriented approach, which examines the ability to deploy resources in the most efficient way to respond to market. As it cannot predict market changes, it instead provides flexibility as it suggests process improvements based on the current organizational capability. Question 3.5 was based on AM's pull-oriented approach based on potential market changes and prepares an organization to adapt quickly and efficiently.

Once the improvement strategies had been determined based on step three, as shown in Figure 2, the solution development phase was initiated. This step pursued a specific solution for an organization after applying the selected improvement strategy. Then, the implementation was based on the knowledge base and the toolbox as well as on the specific needs of the organization. For implementation, a complete design process was performed to provide a specific solution. Moreover, to assess the impacts of the solution before implementing, a simulation would be performed and followed by a pilot phase in a defined scope. Later, a roll-out process for other areas could be initiated based on the example and lessons learned from the simulation and the pilot phase.

Finally, once the improvement project had been implemented, it was be monitored and controlled to ensure that the goals were achieved as well as to enable a continuous iterative improvement of LM principles. Based on the experience of each project, it would be key to review the project and describe what happened in detail in order to learn from each phase and build a knowledge base for long-term successful optimization of the company.

4. Production System Case Study

Firstly, the goal of the case study, the scope, and the methodology were defined. The goal of the simulation case study was to design a generic simulation model for the quantification of cost–benefit parameters for each stage of the optimization sequence. For each specific improvement strategy, a new simulation model was generated in which the simulation logic was adapted according to the differences in the improvement sequence step to which the model was related. The scope of the study was to create:

- A generic simulation model that would serve as a basis for developing specific simulation models. It would provide the required complexity level as well as implement the criteria for later comparisons.
- Specific simulation models for each main step in the optimization sequence determined by the data generated in Section 3, which included LM, SS, TOC, QRM, and AM (i.e., five simulation models plus a model into which no lean method had been introduced). The scope of these models did not include all methods, techniques, and systems within the concepts, but only a selection of them.

The hypothesis of the case study was:

- The improvement of all relevant indicators along the improvement transformation line; this means that a better response of the target indicators is expected after each optimization step starting from the LM implementation and finishing with the AM implementation.

For the methodological framework, the following steps were followed:

1. Definition of the objective, scope, hypothesis, and methodology including a general description of target simulation models and scenarios;
2. Definition of the production system and its flow and characteristics;
3. Definition of quantitative parameters and key performance indicators (KPIs) to obtain results and compare models;
4. Development of the interrelationship among variables within the model;
5. Description of the main assumptions to simplify the complexity of the model;
6. Conditions that made a comparison between models possible;
7. Creation of the simulation models that were dependent on the improvement status;
8. Validation of the behavior of the simulation models;
9. Determination of scenarios;
10. Simulation and extraction of results;
11. Evaluation of the results and conclusions.

4.1. Design of the Generic Case Study

This sub-chapter includes the generic description and specifications of the simulation model case study. The general framework was used for all specific simulation models. This section includes:

- Definition of the production system and its flow and characteristics;
- Definition of quantitative parameters and key performance indicators (KPIs) to obtain results and compare models;
- Development of the interrelationship among variables within the model;
- Description of the main assumptions to simplify the complexity of the model;
- Creation of a generic simulation model based on the logic formulation;
- Conditions that made a comparison between models possible.

4.1.1. Structure of the Simulation Case Study: Production System Flow and Characteristics

Firstly, this sub-chapter describes the general structure of the simulation models that were applied to all simulation models within the simulation case study. The structure was generated to provide the necessary production system flow and characteristics in order to answer the research question. Thus, as can be seen in Figure 3, the structure considered a production system within a supply chain of suppliers–production system–distributors–retailers/customers that served as a generic framework applicable for any sector. Moreover, the production system consisted of technical processes including the transportation, warehousing, and production of finished products as well as management processes, systems, and organizational structure from operational to strategic levels.

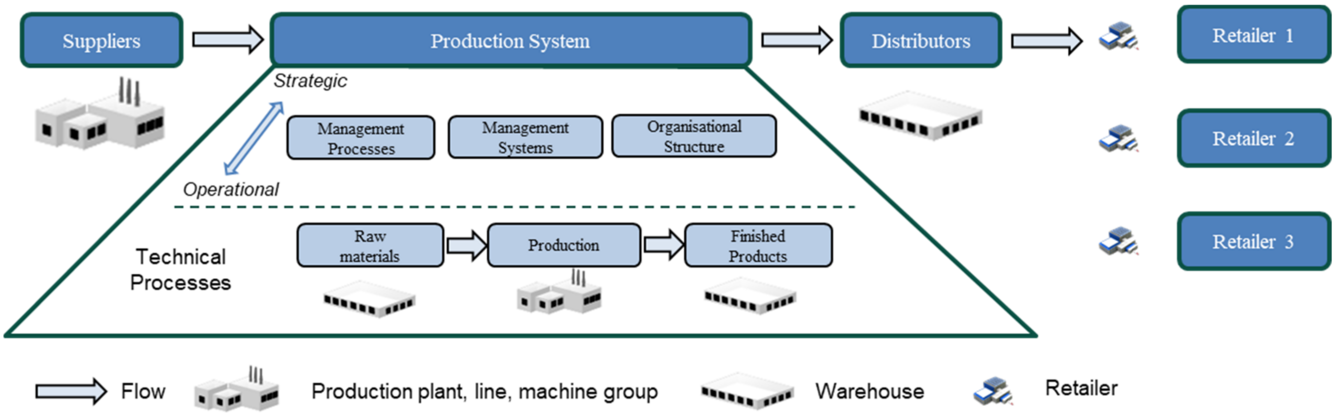

Figure 3. Structure of the simulation case study.

One of the agents within the supply chain are the suppliers, which are represented by production plants delivering the raw materials to the production system. Furthermore, the production system considers one warehouse for the storage of raw materials, three production steps with their respective machine groups and work-in-progress (WIP) inventory, and a final warehouse within the factory with the finished products. In addition, the production system integrates management activities and human resource planning tasks related to production management and the control and execution of the selected production strategies and methods. Then, finished products are delivered to end-customers within the distribution network that consists of a central warehouse and the transportation activities to the retailers. The central warehouse receives all the goods produced by the production facility and stores them. These products are finished, packaged products at this stage, so distribution activities include only those related with the storage and transport of product. As a summary, all models have a set of suppliers, one raw-materials warehouse, three production processes, one finished-products warehouse, a set of distributors, and three retailers serving end-customers that each have a certain demand.

While all simulation models maintained this structure over the simulation period, capacities, methods, systems, human resource structures, and technologies changed depending on the simulation model influencing the model behavior.

4.1.2. Key Performance Indicators

The objectives could be qualitative or quantitative. The research goal was to study the behavior of the different models in different demand scenarios and configurations of a production system. The results were calculated for all model simulations to evaluate the response according to the following key performance indicators:

- Cumulated market demand (# thousand products);
- Cumulated real demand (# thousand products);
- Cumulated production (# thousand products): the cumulative sum of all units produced over the 500 simulated-production weeks;
- Ø Availability of the production plant (%);
- Ø Performance at the final production step (# thousand products/week);
- Ø Quality at the final production step with one-way and no loops (%);
- Cumulated capacity utilization of the production plant (%);
- Ø Labor productivity (products/employee × week);
- Cumulated stocks (# million products);
- Ø Production lead time (# weeks);
- Cumulated service level (%);

- Profits ($ million);
- Cumulated operational costs ($ million);
- Cumulated investment ($ million);
- Return on investment (ROI) (%).

4.1.3. Assumptions

After the problem was defined, we generated assumptions and defined the standard values that informed the models. These provided the basis for the model behavior and how the research questions were determined. First, assumptions were defined to simplify the model with a focus on the simulation goal:

- Time restrictions: first, we defined a time horizon and units of time. In this study, we simulated ten working years, or 500 weeks, to evaluate influences in the medium and long terms.
- Production times for the two products in the supply chain were not variable.
- Times for material transport and employee movements were not variable.
- Distribution of finished products as given.
- Procurement of raw material as given.
- Demand change depended on service level. Therefore, market demand was reduced in quantity of units to real demand.
- Each order had a production unit.
- Bills of materials were not considered.

The following assumptions were made related to the points to be fulfilled in order to conduct a comparison between the simulation models for a defined simulation demand scenario:

- The same demand using replication.
- Same initial situation with no backlog and the same conditions of WIP (products on their ongoing transportation to the customers), the same initial inventory in the different warehouses, and initial inventory ready to deliver to customers.
- Same number of employees with same initial distribution and same capacity to perform warehouse activities.
- Same supply chain distribution network (production facility, warehouses, etc.).
- The warehouses had no stock capacity limitations. It was assumed that outsourcing warehouses could be located with additional costs incurred.
- There were no transport limitations between the different production stages. It was assumed that additional third-party logistics could be found.
- One product unit was assumed to be in a mature stage with stable demand and provided USD 1000/unit of margin. The second product was in the process of being launched and provided USD 2000/unit. These values were used to calculate profits. It was assumed that the new model would have a loss in volume due to unknown future demand.
- The simulation model considered sales loss starting from a customer order lead time greater than 60 days.
- A product was considered a finished product after it left the production facility.

4.2. Design of the Simulation Models Depending on the Improvement Status

It included the description and formulation, logical relationships, and differences within the models. There were many simulation models used to define status along the improvement process. For this study, the simulation models (SMs) were defined as:

1. SMs before lean (status 0);
2. SMs with lean manufacturing (status 1);
3. SMs with six sigma (status 2);
4. SMs with TOC (status 3);

5. SMs with QRM (status 4);
6. SMs with AM (status 5).

Exemplary extracts of the interrelationships and logic between indicators can be seen in Figure 4:

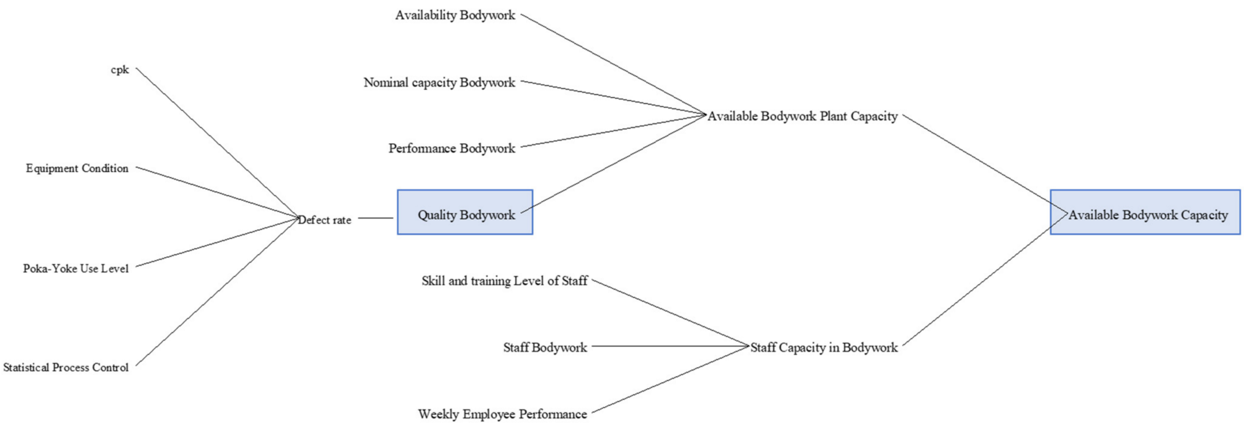

Figure 4. Available production capacity determination: logic and interrelationships among factors (own elaboration).

The simulation models were presented as small incremental cases studies along the transformation process. This meant that the SS effects were added to the LM effects, and, consequently, the LSS effects were added to the TOC implications. The following Table 2 presents the logic of the simulation models.

Table 2. Simulation models' relationships: logic formulation.

No.	Simulation Models	Logic Formulation		
		Situation, Methods, and Techniques	**Description of Impacts**	**Impact on KPIs**
1	Non-Lean	1.1. Processes non-transparent 1.2. Separated kingdoms 1.3. Push strategy 1.4. Reactive quality management (inspection) 1.5. Reactive maintenance management (breakdown-driven)	1.1. Lead times unknown 1.1.–1.2. Information delays 1.1.–1.2. Suboptimal decision making 1.3. Gap between supply and demand 1.3. Unbalanced capacities along the production process 1.4. Unsolved quality problems—unknown root causes 1.5. Production stops, unknown machine condition 1.1–1.5. Lack of continuous improvement	Low availability, performance, quality, and OEE rates Low-capacity utilization Low labor productivity High stocks Long production lead times Low service level High operational costs Low profits High investments Low ROI
2	LM	1. 2. 2.1. VSM 2.2. 5S 2.3. Pull strategy 2.4. TPM 2.5. Poka-Yoke 2.6. Kanban	1. 2. 2.1. Process and lead times known, value is identified 2.2. Waste and condition are visible 2.3. Production system is driven by customer orders 2.4. Improve asset condition 2.5. Avoid production failures 2.6. WIP scheduling and control	Lower operational costs Higher labor productivity Higher profits Lower lead times Better customer service level Higher product quality Higher availability and performance rates
3	(Lean) Six Sigma	3.1. SPC 3.2. TQM 3.3. PDCA-DMAIC	3.1. Process stability and capability 3.2. Increase in customer satisfaction. 3.3. Predictability of production processes 3.1–3.3. Continuous improvement	Higher quality Higher performance Lower operational costs Higher profits Increased productivity
4	TOC	4.1. Five-step TOC improvement process	4.1. Identification of bottlenecks 4.1. Capacity levelling along the production process 4.1. Supply–demand matching	Higher service level Higher system performance Optimal investments or outsourcing costs

Table 2. *Cont.*

No.	Simulation Models	Logic Formulation		
		Situation, Methods, and Techniques	**Description of Impacts**	**Impact on KPIs**
5	QRM	5.1. Time-based competition (TBC) 5.2. Manufacturing critical path time map 5.3. QRM cell	5.1. Time as critical resource 5.2. Knowledge of customer order processing 5.3. Development of the right organizational structure	Lead time reduction Quantification of lead times potentials, i.e., longest critical path 80% of the installed capacity
6	AM	6.1. Rapid partnerships 6.2. Integrated product/production/business information system 6.3. Virtual enterprise	6.1. Information interface with suppliers/customers 6.2. Internal information network 6.2. Adoption of advanced technology 6.4. Facilitates the reconfiguration of the organization	Customer-driven organization increasing its adaptability Improve customer service levels and internal productivity Reduction in response time to market needs

Based on the logic described, the simulation models were developed. Main inputs for the model were the market demand for the products considered, the capacities for supplier, production processes, and distribution as well as the specific settings for the improvement strategy scenario. Output values were the key indicators that were used to evaluate the results. A screenshot of the Vensim simulation model can be seen in Figure 5.

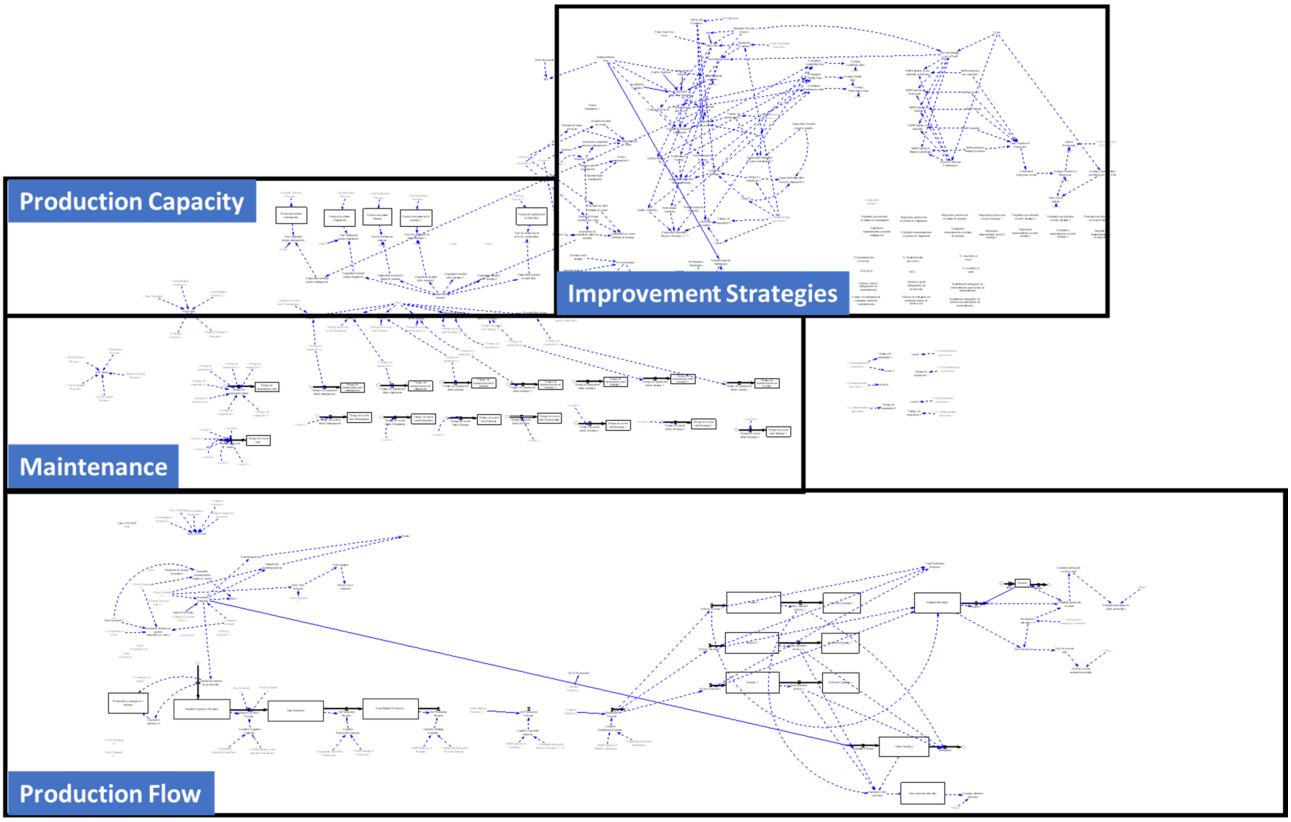

Figure 5. Simulation model structure (own elaboration).

4.3. Simulation Scenarios

There were two simulation scenarios, and they differed only in demand levels: a low and high demand level. The initial supplier, producer, and distribution capacities were the same between both scenarios. The low demand level scenario had 100-unit-less market demand for product in its launching process per week than the high demand level scenario. Both demand levels for the two scenarios considered are shown in Figure 6.

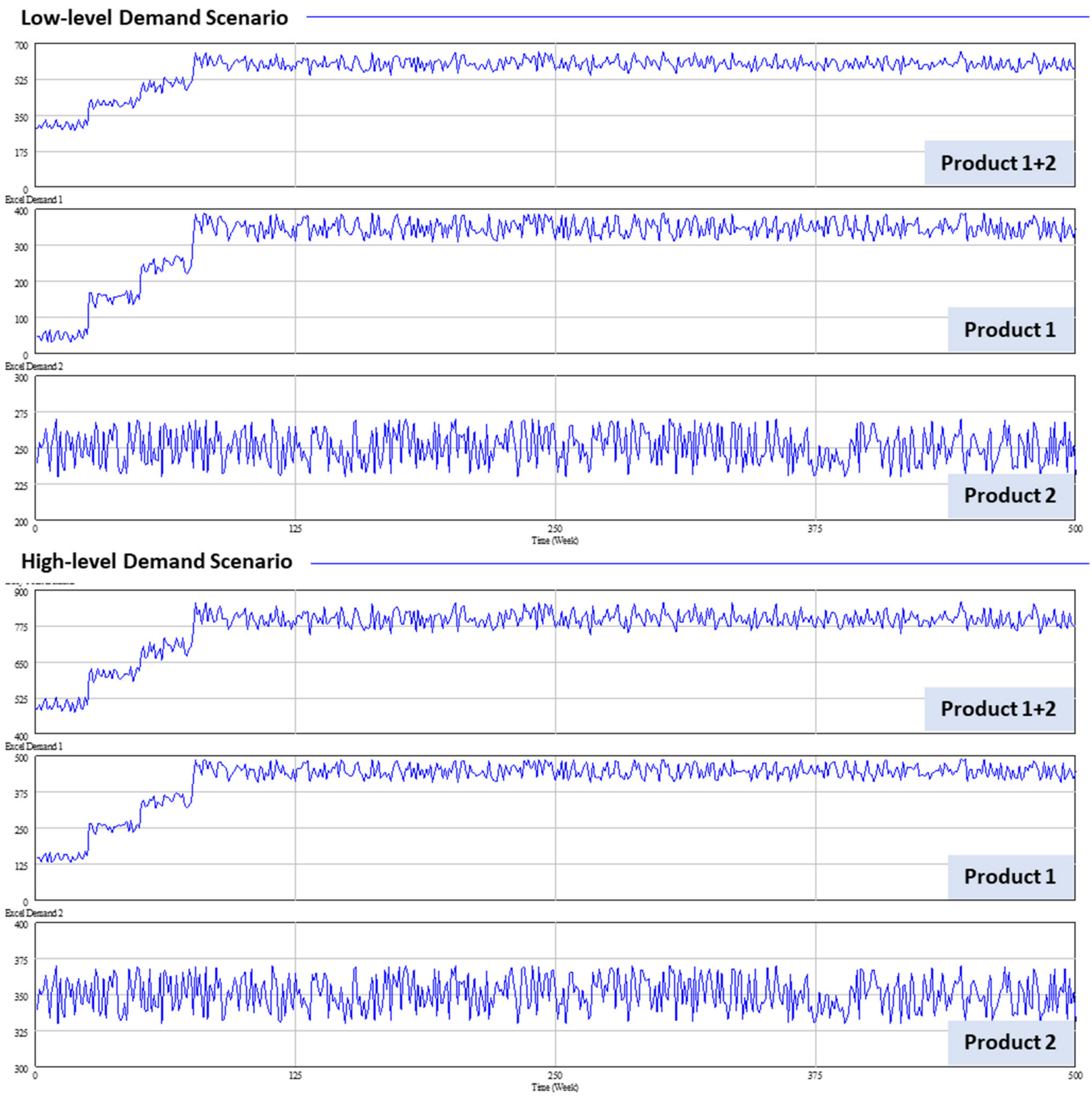

Figure 6. Demand levels in simulation scenarios: low- and high-level demand scenarios.

5. Simulation Results

The simulation results for the low and high demand levels are presented in Tables 3 and 4. In the low demand level scenario, all simulation models had the same demand, but not all of them presented the same real demand (i.e., the effective demand that the company was asked for by its customers). The reduction came from the consequences of poor service levels and long customer-order lead times. As a result, the non-lean model had almost 50% less demand than the AM model. Moreover, total production over the simulation increased from the non-lean model up to the AM model, with the higher increase in production as well as in profits from the non-lean to the LSS model. In addition, availability, performance, and quality rates improved in the simulation models from the non-lean to the AM model. The values for the performance rate responded to the reduction in lead times, which enabled more production with the same resource units. In addition, stock levels reduced significantly up to and including the LSS model, but remained mostly constant from the

TOC to the AM models. Production order lead times decreased from 145 days to 35 days when potential process improvements were applied. Finally, profits increased more than 50% from the non-lean to the AM model, and operational costs decreased more than five times with the higher reduction in the LM model.

Table 3. Simulation results for the low demand level scenario.

No.	Key Indicator	Simulation Models: Cumulative Process Improvements					
		1. Non-Lean	2. LM	3. Lean Six Sigma	4. TOC	5. QRM	6. AM
1	∑ Market demand (# 10^3 products)	284.7	284.7	284.7	284.7	284.7	284.7
2	∑ Real demand (# 10^3 products)	197.7	249.9	283.6	283.8	283.9	284.0
3	∑ Production (# 10^3 products)	170.5	213.7	276.8	281.8	281.8	282.7
4	Ø Availability rate (%)	84.5	90.3	90.3	90.3	91.7	91.7
5	Ø Performance rate (%)	77.8	80.6	96.5	96.5	106.9	117.2
6	Ø Quality rate (%)	82.4	91.4	97.9	97.8	97.8	98.8
7	∑ Stocks (# 10^6 products)	33.9	11.4	2.6	1.8	1.8	1.7
8	∑ WIP stock (# 10^6 products)	1.0	1.1	1.4	1.4	1.4	1.4
9	Ø Labor productivity (products/empl. x year)	34.1	42.7	55.4	56.4	56.4	91.8
10	Ø Production lead time (# days)	145.6	131.3	43.4	35.9	35.8	34.7
11	Cumulated service level (%)	88.7	85.9	95.4	96.7	97.2	97.8
12	∑ Profits (million USD)	270.1	374.5	441.7	442.3	442.3	442.6
13	∑ Operational costs (million USD)	2137	713	566	528	526	421
14	∑ Investment (million USD)	20	20	20	40	40	30
15	Return on investment (ROI) (%)	3.5	4.3	5.0	5.0	5.0	6.9

Table 4. Simulation results for the high demand level scenario.

No.	Key Indicator	Simulation Models: Cumulative Process Improvements					
		1. Non-Lean	2. LM	3. Lean Six Sigma	4. TOC	5. QRM	6. AM
1	∑ Market Demand (# 10^3 products)	384.7	384.7	384.7	384.7	384.7	384.7
2	∑ Real Demand (# 10^3 products)	206.6	281.7	339.0	367.5	381.5	382.5
3	∑ Production (# 10^3 products)	171.3	216.1	283.7	325.7	358.9	367.1
4	Ø Availability rate (%)	84.5	90.3	90.3	90.3	91.7	91.7
5	Ø Performance rate (%)	77.7	80.5	96.4	96.1	106.3	116.5
6	Ø Quality rate (%)	82.3	91.3	97.8	97.4	97.2	98.5
7	∑ Stocks (# 10^6 products)	33.5	22.0	17.4	11.0	5.5	4.8
8	∑ WIP stock (# 10^6 products)	1.0	1.2	1.5	1.7	1.8	1.8
9	Ø Labor productivity (products/empl. x year)	34.3	43.2	56.7	65.2	71.8	119.1
10	Ø Production lead time (# days)	171.6	201.6	124.8	92.1	55.9	43.4
11	Cumulated service level (%)	85.4	77.1	81.8	85.8	90.7	92.4
12	∑ Profits (million USD)	237.8	387.9	502.6	559.6	587.6	589.6
13	∑ Operational Costs (million USD)	2122	1247	1315	1011	754	613
14	∑ Investment (million USD)	20	20	20	40	40	30
15	Return on investment (ROI) (%)	3.5	4.3	5.0	5.0	5.0	6.9

In the high demand level scenario, all the simulation models had the same demand, but not all of them presented the same real demand, as in the previous scenario. As a result, the non-lean model had almost 50% less demand than the AM model. Moreover, total production over the simulation increased from the non-lean model up to the AM model, with higher profits from the non-lean to the LSS model. Furthermore, production increased almost the same quantity from the non-lean to the LLS model and from the LLS to the AM model, which was different from the previous scenario. This meant that LM and SS had more impact when demand levels were low, while they had the same impacts as TOC, QRM, and AM when demand levels were higher. In addition, availability, performance, and quality rates improved in the simulation models from the non-lean to the AM model. In addition, stock levels reduced significantly during all improvement process implementations up to the AM model, where the reduction was a lower percentage than that from the non-lean to the QRM model. This revealed another difference, as compared to the previous model, where the reduction was highest during the first improvements of LM and SS. Production order lead times also reduced continuously. Moreover, profits increased more than 50% from the non-lean to the AM model, and operational costs reduced more than three times with the higher reduction in the LM model. In this second scenario, the changes after the LSS implementation were higher in production, stocks, labor productivity, order lead times, profits, and operational costs. This indicated that when the demand level was higher, there was a capacity bottleneck and a need for lead-time reduction and improved adaptability mechanisms, and, therefore, the relevance and influence on the relevant KPIs of the TOC, QRM, and AM models were higher, as compared to the low demand level scenario.

6. Discussion

As seen from the simulation model and its results, the business process improvement strategies improved the relevant indicators of a production system. Therefore, the optimization sequence should be a continuous and iterative process to achieve the best potential for a production system, given the limitation of resources. Moreover, for developing and implementing an improvement project, many challenges interfere, such as the misalignment of organizational goals, local optimization in place of global optimization, development of new concepts in isolation from other processes and systems, insufficient training level of staff, collaboration hesitancy leading to unknown data, etc. Based on all these reasons, business improvement strategies need to be applied alongside efficient, appropriate project management, which can guide the implementation and determine when and why to do so. Our research was intended to address two basic issues. First, what are the impacts of Industry 4.0 on production systems? Second, what project management methodology could be developed or adapted to consider the optimization sequence presented in the era of Industry 4.0 to implement projects when it is appropriate (right time), where it is needed (right place), with whom (right team), effectively and efficiently (right plan), and with the lowest risks possible while following a prescribed organizational strategy?

6.1. Industry 4.0 Impacts on the Production System Optimization Process

We classified the implications of Industry 4.0 according to the LM system elements, methods, and tools and have been assessed based on their impact on organizational goals, as LM was the basis for the optimization sequences generated by our research. This analysis can be seen in Figure 7. First, the demands on any production system, including the causes of its difficulties and challenges, cannot be drastically changed by implementing Industry 4.0 projects unless the implementation includes substantive, robust, and continuous improvements. Furthermore, the methods used for production will likely remain the same regardless of Industry 4.0 enhancements; however, the external processes and how they interact together may be transformed by Industry 4.0 technologies. Therefore, the production system tools will have to be adjusted based on new technologies that will eventually improve the speed, accuracy, and efficiency of the whole system.

Based on the implications of Industry 4.0 on LM principles, lean strategies will be integral to production processes prior to the introduction of Industry 4.0 technologies. It would not be logical to implement digital systems or advanced processes if the basic process itself has yet to meet the standards required by global production systems.

Since business improvements are time intensive, most companies start with a pilot project. As a result, companies avoid implementing unsuccessful processes and strategies companywide [9]. Simulations are key in anticipating the impact of improvement projects and pilot implementations as well as roll-out projects in other areas. In such situations, the simulation model provides a high value by identifying the optimal balance of cost and investment in exchange for target performance and quality levels. Moreover, the simulation model can provide meaningful insights regarding the most relevant factors and drivers such as implementation time, personnel allocation and organization, resource allocation, distribution, and optimization.

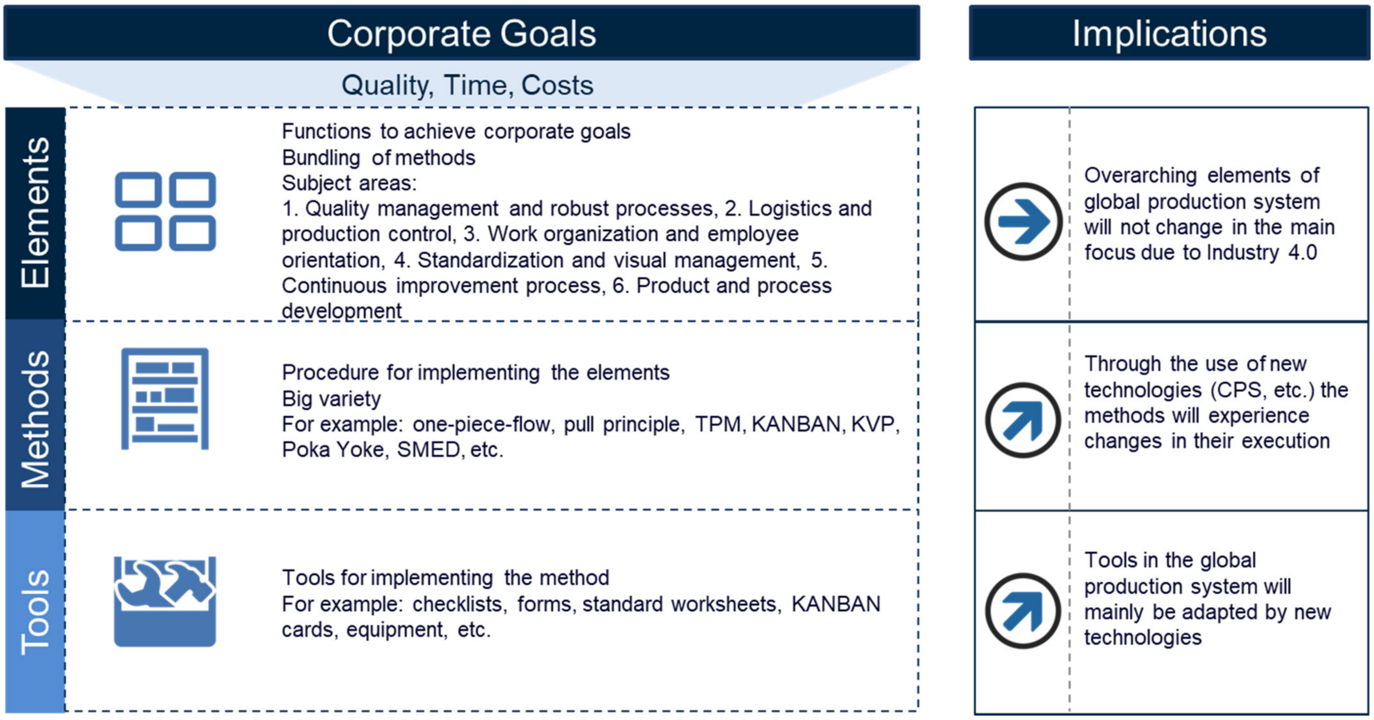

Figure 7. Implications of Industry 4.0 on the lean production system: elements, methods, and tools (own elaboration).

6.2. Improvement Strategies and Industry 4.0 in Project Decision Making and Management

Improvement is good; however, a company has a natural limitation in the quantity of improvement projects that it can have in development at the same time due to the required resources, all while maintaining its internal stability and quality customer service. As a result, organizations have strategies, plans, and decision-making processes that are regulated by internal procedures. Our research examined project decision-making and management paths that could consider many variables and provide accurate information to enable a company to reach its goals.

To generate a solution specific to an organization, the fixed versus the optional stages of the improvement sequence should be identified based on the organization's decision-making criteria, e.g., cost–benefit analysis. To accomplish this goal, managers need to determine in which areas the organization needs to improve its performance or capabilities. By performing this analysis, the focus for future improvement projects can be stablished. Figure 8 provides an example of how this can be carried out. It is based on a socio-technical system that considers three factors: human, organization, and technical. First, the current status of the production system must be identified by analyzing for each capability, together with the improvement strategies already employed and the introduction level of different Industry 4.0 technologies. A maturity level can then be assigned for each capability of a production system. For example, if an organization decides to implement an improvement project that employs RFID technology, they must first know whether or not they have that technological capability before they can develop effective, efficient strategies to meet the target goal.

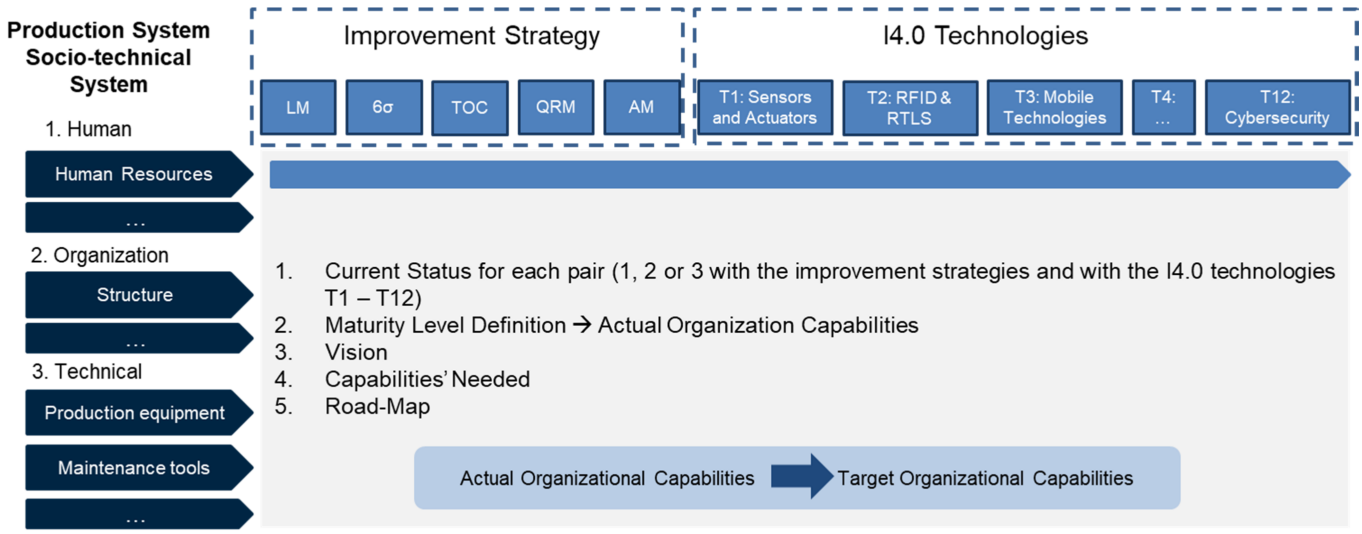

Figure 8. Current production system status: from actual to target capabilities using to the systematic improvement model and Industry 4.0 technologies (own elaboration).

Industry 4.0 encompasses 12 technologies and their capabilities [56], including sensors and actuators, RFID and RTLS, mobile technologies, cyber-physical systems, additive manufacturing, virtualization technologies, simulation, data analytics and AI, adaptive robotics, communication and networking, cloud storage, and cybersecurity [57]. With the help of these technologies, the quality of life for workers as well as the working conditions for people with disabilities can be significantly improved. For example, the implementation of specific technologies in the workplace can assist workers with visual impairments by increasing their mobility and participation in various activities [33].

After having identified the current status of the organization and based on the vision and organizational strategy, target capabilities can be derived. Based on that, and as shown in Figure 9, guidelines for project decision-making and management methods can be determined:

1. Describe the vision, strategy, and future scenarios.
2. Examination of all functionalities or capabilities to reach the vision (e.g., top-down view).
3. Compare target capabilities for all scenarios with actual capabilities.

1. Identify the gaps (e.g., bottom-up view): Based on the comparison, the deficits of the production system can be defined. The gaps could be specific problems of the organization, of a human or technical nature, or related to the manufacturing paradigms in place (e.g., LM or SS), or the current interface between the process and the implemented Industry 4.0 technologies. The gaps could refer to the sustainable interaction of employees with new technologies, to the security of new technologies, to the effectiveness and efficiency of business processes as well as to the information systems and software in use. Industry 4.0 has made digital innovations, products, and services accessible but has almost eliminated the human role in a company's workflow. Industry 5.0, the fifth industrial revolution that is still in its infancy, focuses on human and device cooperation within a production process. Returning the human aspect to the very essence of industrial production leads to workers trained to provide value-added production tasks, thus achieving mass adaptation and personalization of products or services for the end-user. The establishment of a society based on information and communication technologies and focused on the human aspect is a fundamental determinant of the environment of Society 5.0, which will follow the development of Industry 5.0 [58]. Moreover, it is crucial to choose the optimal information and communication services that will be required for the process

relationships among elements, people, and stakeholders, as it is fundamental for any future success in process improvement [59].

2. Evaluate the gaps: The implications in the systems and in the different scenarios–priorities to them. Determine what needs to be addressed first in relation to organizational strategy and management goals.
3. Define project alternatives to close each gap in order to develop a roadmap of projects according to the priorities and based on time and budget constraints. For that purpose, the developed systematic business improvement model can be applied. Identify if, for this specific business improvement process, Industry 4.0-related technologies are needed to reach the target level and if they are compatible in parallel or in sequence. Alternatives can be one of the following three types:
    a. Improvement strategies;
    b. Industry 4.0 technologies;
    c. A mix of improvement strategies and Industry 4.0 technologies, in sequence or in parallel.
4. Determine if the current improvement strategies and availabel technologies in the market are capable of closing the gaps. If they can, assess which ones and how to implement them. If not, the development of an improvement strategy that will either address the deficiencies or work with them is required.
5. Assess the potential project alternatives while considering expected sequence steps including related Industry 4.0 technologies, tools, or systems to be implemented as well as human resource requirements. In fact, the European industrial structure is undergoing a transformation in the management of digital and other new technologies and new business models. Smart manufacturing systems (SMS) have attempted to maximize the productivity, the agility, the sustainability, and the quality of manufacturing through the intensive use of advanced contemporary technologies, especially information and communication technologies, along with intelligent software applications [60].
6. Employ decision making based on predefined criteria. For example, investments and costs with risk and viability levels should be assessed and defined. The risk concept has to be expanded as a consequence of technological development in order to consider security as one of the issues that need to be addressed continuously. Cyber threats are significant when adopting the Internet of Things technologies, and with its growth, the threats will continue to increase due to their dynamic nature, which implies the need for dynamic security solutions capable of adaptation [61].
7. Coordinate a project team and project kick-off meeting.
8. Conceptual phase: This involves the conceptual development of a solution for a specific problem or for a future capability that will be required and/or benefit the organization. Interviewing personnel at different levels and acquiring their insight will improve the overall outcomes and allow the organization to adapt more effective strategies based on a deeper awareness of the challenges that may be involved. Moreover, specialists and experts may need to be recruited as consultants to assist in designing a stronger foundational concept.
9. Pilot phase: This phase consists of proving the benefits and increasing the likelihood of a successful outcome for potential improvements and technologies as well as revealing unexpected challenges and difficulties that will need to be addressed. The involvement of improvement and technology experts may be required to discuss and define the areas of action with higher potential as well as for the identification of high-impact and low-resource potentials. After the pilot or testing phase, the potentials can be compared with the target outcomes defined when the project was designed, such as the capabilities, the implementation time, investment and cost levels, etc.
10. Roll-out phase: This phase establishes the appropriate processes and technologies for a global production system. There should be always a decision-making point

after which the project will continue with the roll-out organization-wide, or it will be suspended. Factors may change or unexpected issues may arise that may highly influence this point of decision.

11. Management, control, and continuous improvement: continuous improvement and review of the capabilities and cost–benefit application of each project is crucial for long-term success.
12. Develop a knowledge base: Recording the progress and feedback during the implementation of an improvement project can support future improvements and enable organizations to more accurately predict their success. In addition, developing expert systems and customizable solutions as well as enacting industry best practices are critical elements for competitiveness in any industry.

Figure 9. From strategy to the decision making and management of improvement and Industry 4.0 projects (own elaboration).

7. Conclusions

Based on the research performed, current research gaps were successfully indicated based on the literature review. Moreover, the need for integration of the different improvement strategies was demonstrated. In this context, the characterization of relevant improvement strategies provides an overview of their utility based on their focus, scope, principles, and tools. On this basis, the systematic improvement model served as a conceptual research framework for the design and optimization of existing production systems.

From a managerial point of view, current challenges of manufacturing systems were described, and the conceptual model showed potential as a guide for managers for identifying challenges, creating vision for Industry 4.0 improvements, developing a plan for optimization as well as how to assess and initiate projects. Moreover, it provided the needed information to determine which steps and improvement strategies were more appropriate to be selected for the specific needs of the production system. Furthermore, Section 6 provided a framework for the development of improvement projects that include Industry 4.0 technologies. Moreover, it provided a holistic approach to the decision-making process based on the capabilities that exist within an organization and those that will be required for optimization.

To prove the utility of a new conceptual model, simulations with different improvement sequences according to the developed systematic improvement model were generated. Based on the model, the simulations, and the results, the following statements can be concluded:

- All the steps along the process provided an improvement in KPIs.
- Higher improvement was dependent on market need.
- When the internal capabilities were the constraint, the TOC as well as the QRM and the AM principles performed better overall on the experimental production system.
- When the market was the constraint, lower demand defined the capacity of the production system, and LM and SS provided better performance overall, as they improved the process effectiveness and efficiency as well as the quality, which are directly related to improved customer satisfaction, service levels, and experience and have the potential to increase the demand for more volume. In these cases, QRM also provided improvement if lead time was the cause of the low demand. Moreover, if the markets were not stable and major disruption had been indicated, AM provided the capability to react to them even while KPIs were required to improve.

Some of the research limitations are that the sequence steps of the conceptual model consider relevant improvement strategies; however, other tools and methods also exist and are not included in our research. Moreover, the simulation model was a generic model with reduced complexity, and Industry 4.0 is only discussed in this paper and was not demonstrated in the models or simulations.

In this case, future research can lead to the implementation of the conceptual and simulation models for real production systems and managerial decision making as well as to apply the methodological project framework for selecting improvement projects. Additionally, the development of the model with other improvement techniques and strategies can be considered as well to include other factors in the process improvement strategies and project selection by integrating human–machine interaction and sustainability aspects such as the improvements availabel for people with disabilities in Industry 4.0 environments, security and cyber-security requirements, and data as well as software development and maintenance. In addition, the design of a key performance system that enhances the current focus on supply chain and economic goals by considering other relevant factors such as working conditions, indicators of security, sustainable operations, etc., is necessary

In summary, our research demonstrated the potential benefits of determining an organizations state, assessing the potential improvements and implementation methodologies, and identifying and implementing projects for the continuous improvement of a production system aligned with the defined organizational strategy. As a result, the proposed methodology may prove to be a useful tool for organizations and managers as they develop roadmaps that secure their long-term viability.

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