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Implementation of an Industry 4.0 Strategy Adapted to Manufacturing SMEs: Simulation and Case Study

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Abstract: Quebec's small- and medium-sized enterprises (SMEs) in the manufacturing field are facing a major challenge: implementing a successful digital transformation in an increasingly competitive world, with a labor shortage and customer demand for highly customized products. Technology is a leading solution for improving competitiveness. However, the tools and subsidies available offer little in terms of results for these companies, which have neither the prerequisites nor the resources to successfully carry out their digital transformation. This research aims to develop an adapted Industry 4.0 strategy for manufacturing SMEs reorienting themselves toward mass customization. It seeks to demonstrate that agility and modular design are prerequisites, and it advocates for individual assessments as success factors. The research presents the development of such a strategy for manufacturing SMEs. A case study in the form of action research, combined with a simulation-based experimental design based on a sample of one Quebec manufacturing SME, serves to validate the implementation of the adapted strategy. This research emphasizes the importance of lean, agility and modular design concepts and of individual assessment for successful Industry 4.0 implementation in SMEs. Future research could systematize modularity management in the Industry 4.0 era to boost SME competitiveness.

Keywords: Industry 4.0; agility; modular design; Quebec manufacturing SME; customized mass production; strategy

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1. Introduction

Many of Quebec's small and medium-sized manufacturing companies have been overwhelmed by the external disruptions that were accentuated during the COVID-19 pandemic. These disruptions have affected supply chains and economic stability, forcing these companies to react quickly to maintain their competitive edge. In Quebec, this challenge is further exacerbated by a labor shortage and lower productivity levels compared to other regions. Therefore, this article focuses specifically on Quebec's SMEs, aiming to address these unique challenges through targeted strategies for Industry 4.0 implementation. In response, they are trying to modernize by implementing Industry 4.0 technologies, but this approach can seem risky and complex. How can they approach Industry 4.0 strategically to ensure successful implementation?

Companies need to distinguish themselves in a globalized world and offer a range of products to meet customized demand. Many growing companies are moving from a customized production strategy to a customized mass production strategy in order to remain competitive in today's uncertain environment. They are looking for innovative solutions to improve their productivity and efficiency. To this end, current subsidy programs address the need for innovative solutions by encouraging companies to adopt Industry 4.0 technologies and carry out diagnostics. Despite the tools and subsidies in place, only 14% of companies consider themselves totally satisfied with government support measures to facilitate digital transformation [1]. This suggests a lack of effective implementation strategies to help companies know where to start and how to take action.

Industry 4.0 research is gaining more and more ground in terms of success factors and barriers [2], the prerequisites and level of technology implementation in Quebec [3,4] and maturity models [5–7]. Despite the advancement of Industry 4.0 research on SMEs, the literature contains few case articles on Industry 4.0 implementation supported by observations [8]. Moreover, SMEs often face resource constraints such as limited time and financial capabilities, making the adoption of Industry 4.0 technologies a significant challenge. It is crucial for SMEs to implement Industry 4.0 to remain competitive in the rapidly evolving market, but the benefits of Industry 4.0 are not quantified for SMEs in the literature [9]. The literature does not document the adaptation of Industry 4.0 implementation models or strategies in SMEs [10], thus leaving an opportunity for research. Companies implement Industry 4.0 principles without supporting evidence. The lack of literature concerning strategy and business application cases, combined with the technology focus of access grants, may explain the low success rate of Industry 4.0 implementation. The Industry 4.0 implementation success rate would be improved by developing strategies for SMEs adapted to mass customization aimed at creating a competitive advantage while integrating previous research.

Utilizing standardized modules not only shortens the time to the market but also reduces the number of components needed. This reduction translates into fewer transportation needs due to the decrease in product variety, which promotes sustainability. Furthermore, modules offer an extended lifespan, ensuring an increase in both product quality and reliability, leading to sustainable production.

This article addresses the lack of literature identified previously by demonstrating the adaptability of an implementation strategy in a Quebec manufacturing SME to help it successfully transition to customized mass production. This article focuses on adapting the approach for companies that want to successfully transition from custom manufacturing to personalized mass production. The adaptation is based on lean, agility and modular design concepts, where lean aims to eliminate waste, agility aims to respond quickly to market changes and modular design aims to use interchangeable components. These important elements should be considered prerequisites or tools for achieving mass customization. This study has three primary objectives: to propose an Industry 4.0 implementation methodology, to validate this methodology using a company case study in the form of action research and to validate the subsequent stages of the methodology via a simulation-based design of experiment. This simulation aims to replicate the company's production to validate the effects of the variables defined in an adapted strategy. The research aims to answer the following key questions: Which components of Industry 4.0 should be implemented in Quebec's manufacturing SMEs in the context of mass customization? Which interventions achieve the agility needed for the implementation of Industry 4.0? How should current Industry 4.0 strategies be adapted to guide SMEs transitioning toward mass customization? This study is part of a broader research project aimed at developing a universal adaptive strategy for implementing Industry 4.0 in different types of SMEs. This project presents four Industry 4.0 implementation case studies in high-tech manufacturing SMEs, namely Nita, Robivec [11], Métalus [12] and Robovic (present study).

The following sections present, in order, the research context (Section 2), the corporate case (Section 3.1), the strategy adaptation (Section 3.2), the case study methodology (Section 3.3), the experimental design and its variables (Section 3.4), the simulation based on the corporate case (Section 3.5), the experimental design results (Section 4), the discussion of results and suggestions (Section 5) and the conclusion (Section 6).

2. Research Context

SMEs face several challenges in adapting Industry 4.0 to their reality in a context of mass customization and increased competitiveness, particularly in terms of choosing which tools and practices to implement. This article analyzes the literature to highlight the barriers to, prerequisites for and technologies of Industry 4.0 and to demonstrate that an implementation strategy can be adapted to an SME.

2.1. Research Context Methodology

Relevant articles were selected using a query on the Scopus search engine using the keywords "4.0" and "SME" for the years 2018 to 2022. The 210 most relevant articles were selected based on the article titles from the 696 documents found. The articles were categorized according to their subject and their relevance for defining the components to be included in an implementation strategy. The 18 articles in the most relevant categories were analyzed to design the research context matrix. Some references cited by the analyzed articles were added to this article's references. The same search method was used for the research context on agility and modular design presented in Section 2.4 using the keywords "customization", "mass", "agility" and "SME". No date filter was used for the research context on agility and modular design, as these are enduring concepts that we aim to apply rather than recent advancements.

2.2. Definition of Industry 4.0

Industry 4.0 can be defined as the new industrial revolution encompassing a set of technologies and organizational approaches affecting products and the production process. This set of practices and technologies brings the company's players and machines into an interconnected environment where they exchange information in real time [13,14]. Industry 4.0 technologies have been shown to improve quality, delivery, flexibility and cost performance in manufacturing SMEs, thus improving the competitive position of manufacturing companies. These technologies push SMEs toward improvement by setting a new performance standard [15].

2.3. Identifying the Tools and Practices for Adapting an Industry 4.0 Strategy to SMEs

To define the tools to be put in place as part of an Industry 4.0 implementation strategy, the basic Industry 4.0 components available to SMEs at the start of this transition need to be identified.

Porter and Heppelmann [16] identified four uses for technology: monitoring, control, optimization and autonomy. It therefore seems logical to initiate the transition to Industry 4.0 with monitoring and control technologies. With this in mind, the Internet of things (IoT), cloud storage and radio-frequency identification (RFID) technologies are prioritized, not only because they are more affordable and therefore more accessible to SMEs [9].

Cloud storage and computing is identified as the most widespread technology among SMEs [9]. Uses of this versatile technology include document sharing, adding services to the manufactured product, collaboration, production distribution and resource optimization.

According to Gamache et al. [3], using an enterprise resource planning (ERP) system, manufacturing execution system (MES), real-time key performance indicators (KPIs) and a knowledge management system is essential for manufacturing SMEs. Schönfuß et al. [17] added that many SMEs also need to focus on data collection and observation in order to successfully implement data-integrated technologies.

Pech and Vrchota [18] supported these authors in prioritizing data analytics, cloud storage and computing, Operator 4.0, ERP and MES, viewing them as pillars of Industry 4.0 for SMEs. These technologies and concepts form the foundation on which companies can build their transition.

SMEs need tailored, low-cost and simple solutions [19]. Some expensive technologies, such as artificial intelligence, machine-to-machine connectivity and virtual reality are less common in the literature and appear to be less of a priority for SMEs [8,20]. Pech and Vrchota [18] supported this idea by prioritizing technologies such as virtual reality, data sharing, artificial intelligence, machine interconnectivity, mobile technologies and robots in the second and third phases.

We can conclude from the literature review that the technologies and practices that are most accessible for SMEs to implement as part of an Industry 4.0 implementation strategy are cloud storage, manual data collection tools at the outset, implementing an ERP and MES system, and data analysis. Once these basic technologies and practices have been implemented, more advanced data collection technologies, such as the IoT, automate data collection as part of monitoring.

Finally, some authors have argued that it is important for SMEs to consider not only technologies but also organizational factors and other principles for implementing Industry 4.0 that are strongly linked to mass customization.

In particular, according to Gamache et al. [3], Industry 4.0 is based on business practices such as agility and innovation. Menon and Shah [21] identified design principles, which include modular products, service orientation, vertical and horizontal integration and real-time capability, as essential components of Industry 4.0. These design principles align with the idea of increasing business agility. Thus, we can conclude that technologies are essential for implementing Industry 4.0 but that other pillars are also required.

In conclusion, the elements necessary for mass customization, such as agility and modular design, are also key to implementing an Industry 4.0 strategy.

2.4. Agility and Modularity

This section of the research context focuses on the importance of Industry 4.0 in the transition to personalized mass production. However, Industry 4.0 alone is not enough to steer a company toward mass customization. Agility and modular design are key to this transition and are also essential in implementing an Industry 4.0 strategy. These concepts are introduced in this section.

Vázquez-Bustelo et al. [22] defined agility as a production model that responds to changes in the environment by providing flexibility, speed, quality, service and efficiency. The main agility concepts are flexibility, responsiveness, virtual enterprises and information technology, according to Gunasekaran and Yusuf [23]. The concept of agility, which emerged in the mid-90s, differs from lean philosophy by encompassing reconfigurability and adaptability in the face of turbulent environments [24]. Agility is therefore essential to making companies dynamic in a constantly changing market [25]. It is interesting to note that agility and lean, although distinct, can complement each other when implementing Industry 4.0 [26]. Accordingly, lean can be used as a preparatory or complementary tool when implementing Industry 4.0, reinforcing the benefits of both lean and Industry 4.0 approaches.

Nevertheless, it is important to understand that Industry 4.0 is not simply about increasing organizations' agility, but also steering businesses toward increase customization [19]. To this end, modular design complements agility in orienting companies toward mass customization. Modularity is defined as a flexible assembly of independent standard modules to create various end products through different configurations [27]. Tools such as modular design help make the transition from engineering-to-order to assemble-to-order by providing better management of product variety [28]. Implementing a constant work-in-process (CONWIP) system can facilitate the production of frequently used modules and make it possible to produce optional modules on demand [29]. These same authors proposed a strategy for producing modular products that consists of codifying part drawings, creating a modular bill of materials (BOM) and planning production based on project management and according to the modules' critical path. In addition, standardizing parts into modular structures offers advantages such as simplified production planning, reduced set-up times and optimized economic order quantities [30]. Combining agility and modular design thus enables companies to respond more effectively to customized demand while maintaining efficient production.

The Just-in-Time (JIT) philosophy and its set of tools, such as reduced set-up times and the Kanban concept [31], are also useful for increasing agility [23] and managing standard parts. To manage standard parts and module production batches in CONWIP after changing from engineering-to-order (ETO) to assemble-to-order (ATO), a flexible layout [24] and dynamic cells, which facilitate the implementation of modular structures [19], are also key to adapting to small production batches. In addition, integrating with suppliers [32,33] and establishing network companies, which are collaborative networks of SMEs aiming to optimize resource use and manage product variety [19], can help improve agility. Industry 4.0 technologies can enhance agility and modularity tools by providing, for example, real-time data analytics for networked enterprises or production planning, making companies more reactive. These technologies can be the subsequent steps in specializing the company and increasing sales.

An accumulation of technologies does not necessarily guarantee increased agility [34]. In fact, to progress toward agility, these technologies must be combined with improvements in workers' skills, know-how, processes, partnerships [35] and an appropriate strategy and corporate culture [23]. Employee training and change management strategies are vital in this context, helping facilitate the adoption of new technologies, agility tools, lean practices and modular frameworks. It is important not to overlook the human aspect of this transition.

In short, to successfully transition to customized mass production using Industry 4.0, an implementation strategy must take into account agility and lean principles, modular design, integration with suppliers, implementation of the network enterprise concept and improvement of internal skills and processes.

2.5. 4.0 Prerequisites for SMEs

Many companies lack the understanding and resources to embrace the transition to Industry 4.0 [36]. The centralized decision making often characteristic of SMEs, especially family-owned companies, may impede internal process changes [33], which is likely to reduce the success rate of Industry 4.0 implementation. Drawing upon Industry 4.0 tools and practices, as well as the previously discussed principles of agility and modularity, prerequisites are intended to overcome the challenges of implementing Industry 4.0 in SMEs and contribute to a holistic approach by improving efficiency and productivity [8]. By starting with smaller projects requiring little or no technological knowledge, companies can increase productivity and free up resources for larger projects later. Small projects could include adopting practices such as lean and agility tools, which are low-cost and require little technological knowledge [11,12]. Moreover, lean and Industry 4.0 must be considered together to achieve operational excellence [9]. To achieve the agility level required to implement Industry 4.0, real-time access to production data, a broadband Internet connection, worker training and stakeholder commitment to the project [4,37] are necessary. Defining a strategy is also essential to a successful transition [38], leading to an action plan that includes tools and practices such as lean and agility. When companies implement these prerequisites, they establish a culture of change and a structure for change management, and they increase in-house technological knowledge. Companies can begin by undertaking smaller projects, such as optimizing inventory through JIT or via Kanban systems, reducing set-up time with the single-minute exchange of die (SMED) technique, and many more, to incrementally free up resources and increase productivity. The effectiveness of these small-scale initiatives can then be measured using KPIs like lead time reduction, number of projects delivered per period and cost savings, thus preparing for the implementation of large-scale projects, such as those of Industry 4.0. Real-world examples such as the study by Abdulnour et al. [12] illustrate how SMEs can successfully implement these prerequisites for a smoother transition to Industry 4.0.

2.6. 4.0 Implementation Strategy for SMEs

An Industry 4.0 implementation strategy can be developed for the context at hand by considering the prerequisites for freeing up resources, the technologies accessible to SMEs, and the tools and practices leading to a successful transition to customized mass production.

Ghobakhloo [39] raised the need for an Industry 4.0 implementation strategy, defined in their article as identifying and planning steps, a time scale, costs and benefits based on a clearly established objective. According to Mofolasayo et al. [40], creating a suitable strategy is a complex task, requiring a number of factors to be taken into account, including the choice of technologies, the order in which they are implemented, the size of the company, its financial situation and its internal policies. These same authors suggested using a structured, step-by-step approach to establish a solid foundation prior to Industry 4.0 implementation. Accordingly, any strategy should be step-by-step and include an approach, a choice of technologies and projects, an implementation sequence and the company's desired goal or direction.

There are several existing step-by-step approaches for implementing Industry 4.0. Sufian et al. [41] proposed an approach that encompasses components such as strategy, connectivity, integration, data analytics, artificial intelligence and growth. Ghobakhloo et al. [42] suggested five conditions for technology implementation: knowledge and skills, internal technological maturity, value chain readiness, internal management skills and external support for transformation.

Based on the work of Ducrey and Vivier [43], Bouchard et al. [11] and Abdulnour et al. [12] presented a six-stage approach that was validated in manufacturing SMEs: (1) the preliminary stage (develop a vision and strategic planning, map the value chain), (2) the audit stage (answer the proposed questionnaire), (3) the plan stage (identify sources of improvement and prioritize projects), (4) the test stage (implement digital and non-digital recommendations), (5) the deploy stage (deploy digital and non-digital solutions) and (6) the optimize stage (correct, optimize and implement the next project). This different strategy includes an audit, a list of pre-established recommendations and a process for adapting a strategy for SMEs, taking into account digital and non-digital elements. In particular, the audit and list of pre-established recommendations proposed take into account several prerequisites, as well as mass customization, notably through product standardization and modularization. Bouchard et al. [11] studied the implementation of modular product design, product and part coding, the introduction of ERP, Kanban inventory management, dynamic cells and an orientation toward e-commerce technologies. These improvements helped the company move toward Industry 4.0. Abdulnour et al. [12] focused on integrating agility and lean principles within the framework of Industry 4.0. They implemented standard work methods, a skills matrix, reduced set-up times, bottleneck improvement, 5S (sort, set in order, shine, standardize, sustain) practices and transport carts for parts. Following these lean interventions, the company turned to mass customization tools, such as modular product design, implementing dynamic cells and step-by-step production automation, notably through the use of cobots. These two cases reveal that this strategy seems more suited to SMEs undergoing a transition to mass customization, especially when they have limited resources and are not fully ready for Industry 4.0. Indeed, using the same methodology while employing different tools and technologies highlights the importance of adapting a strategy's tools and objectives to meet the needs and reality of each company. A strategy based on implementing prerequisites, agility and modular design before moving on to the technologies available to SMEs enables companies to move toward customized mass production and increased productivity.

The existing literature on Industry 4.0 in SMEs primarily focuses on technologies, with limited exploration of mass customization and a notable absence of a clear implementation methodology for SMEs. The prerequisites for Industry 4.0 adoption in SMEs, such as initial assessments and preparatory initiatives, are often neglected, leading to an absence of comprehensive actionable guidelines for organizations, which extends beyond just Industry 4.0 initiatives. Moreover, the human factor and empirical validation seem often overlooked, indicating a need for more comprehensive research. Finally, the existing literature leaves an empirical void that could be filled by case studies and sector-specific examinations. The hypothesis of this study is that an Industry 4.0 implementation strategy based on agility and modular design can facilitate the successful transition to mass customization in SMEs. To address gaps in the literature, the company case described below, on which the rest of the action research business case is based, is unlike any in the literature.

3. Theory/Case Study

As shown in the research context, modular design increases agility. Lean and agility concepts are prerequisites to Industry 4.0. Industry 4.0 implementation then increases the company's agility level. By first adopting agility, lean philosophy and modular design, enterprises establish a foundational framework that prepares them for more intricate changes like Industry 4.0 technologies. When an Industry 4.0 strategy is adapted based on Industry 4.0 prerequisites, agility and modular design, many critical concepts needed for mass customization and Industry 4.0 are simultaneously considered. This section presents a company case, the adaptation of an Industry 4.0 strategy and its application in action research based on important concepts found in the research context.

3.1. Company Case

The selected company is a small metal fabricator with around 50 employees located in central Quebec that designs, manufactures and installs automated palletizing, case packing and bulk bag filling solutions. Its wide range of equipment is custom-designed and involves a high degree of diversity and customization complexity. Its solutions can pack and palletize a wide range of products varying in size, weight, type of container or pallet and can be adapted to liquids, solids or powders. These variations lead to multiple changes in the technical specifications of all the equipment used. The company used the engineering-to-order model and did not rely on inventory to meet customer demand. The organization had undergone a limited number of changes in recent years.

The company was delivering 10 to 15 projects per year. The normal delivery time was 20 to 26 weeks. The waiting time for orders was getting longer and longer as demand grew and was then more than 52 weeks. The bottleneck was project design and drawing. Although design and drawing could be outsourced, the company found it cost-prohibitive. The case study was conducted just after the COVID-19 pandemic, which also contributed to supply difficulties and increasingly long delivery times, making it more and more difficult to deliver projects on time. Reaction times were getting longer, with some critical parts taking longer than normal to deliver, in addition to part shortages. Figure 1 shows the different stages in the company's order process.

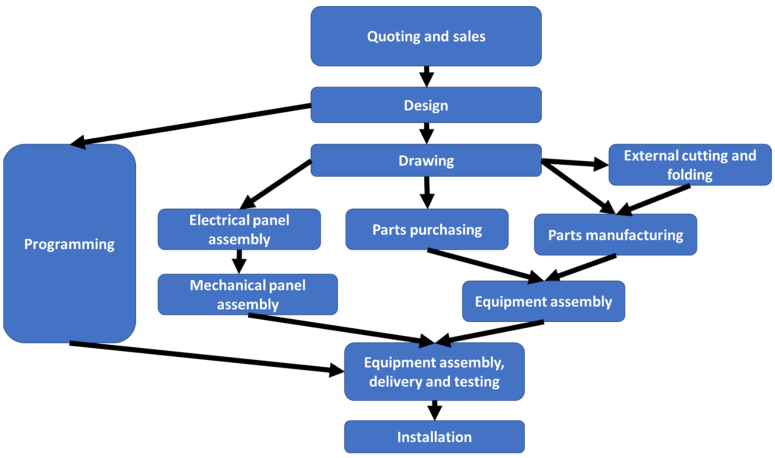


Figure 1. Diagram of the main stages in the company's order process.

The company's objectives were to transition to configure-to-order (CTO) or assemble-to-order (ATO) production, increase production capacity, reduce manufacturing costs and decrease reaction time while maintaining a constant number of workers. Productivity is used to assess the impact of the Industry 4.0 strategy in this research. The following section explains how the Industry 4.0 implementation strategy was adapted to this specific context. The strategy includes identifying which tools and practices to employ, the implementation sequence and the steps for meeting the company's objective in the context presented.

3.2. Adapting a Strategy

To meet the specific needs and context of the company studied, the Industry 4.0 implementation strategy proposed by Gamache (2019) was adapted based on the key considerations identified in the research context, i.e., selecting and prioritizing specific tools, practices and technologies, as part of the company's strategic plan. Accordingly, a basic strategy could be adapted by modifying the technologies selected, the projects carried out and the objectives set in line with the strategic plan or by modifying the approach according to the company's specific context.

The strategy was adapted using Gamache's six-step approach but was further adjusted to go beyond the framework of Industry 4.0 implementation to also consider the specific limitations of the company studied, as well as the context of orientation toward mass customization and increased competitiveness.

3.2.1. Preparation Phase

The first two stages are the preliminary stage, which includes an initial assessment of the company's current Industry 4.0 capabilities, and the audit stage, which consists of an in-depth analysis of the company's operations to define a clear plan for the transition. These two stages are intended to implement the prerequisites for Industry 4.0. Agility and modular product design are key to ensuring that the adapted strategy meets the need for mass customization while increasing productivity.

3.2.2. Digital Transformation Phase

The company then begins its digital transformation with stages three to six of the selected approach: plan, test, deploy and optimize. Technologies are deployed progressively through individual projects, in parallel with the implementation of agile and lean tools, as well as other selected practices. The tools selected for this strategy are those that the methodology dictates should be implemented first in the target SME, although other technologies are available and of interest to the company. These projects were selected based on the value chain mapping and audit conducted in Stage 1. The research context and the company's strategic plan were used to validate project selection and alignment. Project sequencing was conducted with the company, considering the level of technological knowledge required, precedence and benefits for the company. The adapted strategy is illustrated in Figure 2, where the tools and practices, the two phases of the strategy and the project implementation sequence are clearly identified. The two colors represent the two different methodologies used: action research, which is a collaborative problem-solving mechanism involving real-world business case interventions and evaluations, for the first part of the strategy, and simulation-based experimental design, which employs computational modeling to test multiple solution interactions under controlled settings to validate the subsequent stages. These methodologies are detailed in the following sections.

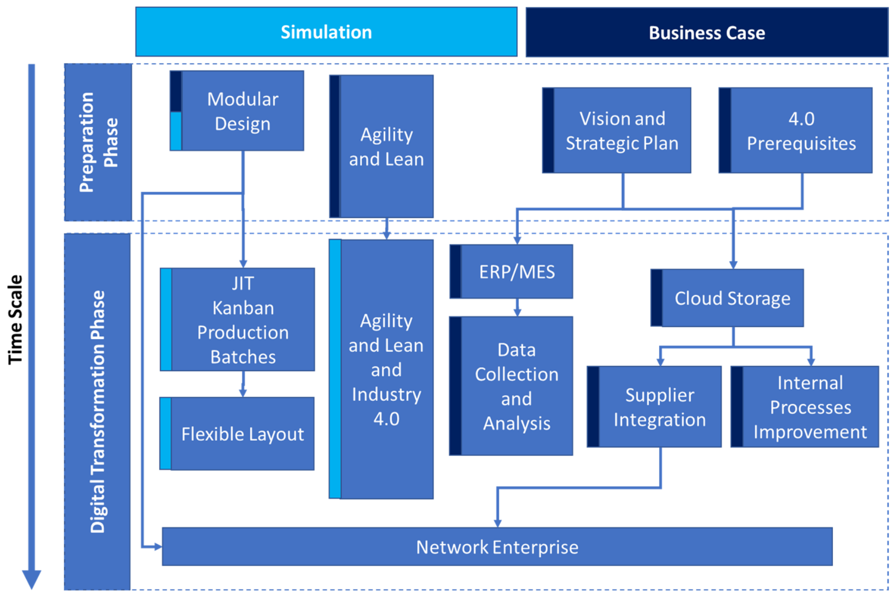


Figure 2. Projects and milestones in the adapted strategy.

3.3. Case Study Methodology

As part of this corporate action research, several implementations were carried out to improve operational efficiency and facilitate the transition to Industry 4.0. Each implementation corresponds to a project defined according to the digital transformation strategy established in the previous section. Figure 3 below shows the projects carried out in the first part of the methodology, consisting of nine solutions grouped into three parallel groups. It also shows the chronology of the implementation stages, in descending order. Details of the implementation of the improvements shown in the figure are described below.

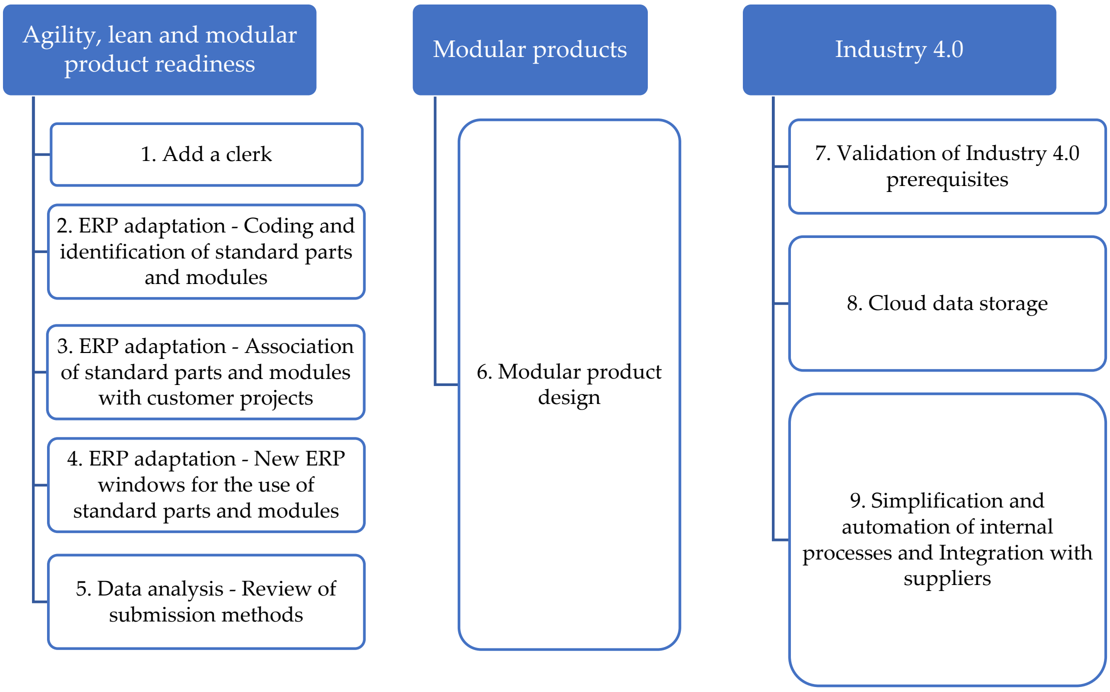


Figure 3. Diagram of projects implemented in the company case study.

1. Adding a clerk to feed workstations improves the efficiency rate of value-added workstations, thereby making production and assembly resources more efficient. Further lean and agility projects are analyzed in the simulated experimental design plan.
2. A new parts and modules coding system was developed in line with the company's specific needs, making searching for parts and modules quicker and more efficient. In addition, the project increased the standard parts reuse rate.
3. A system for reserving standard parts and modules was implemented, leading to better management of the use of these parts and avoiding production start-up errors. In addition, labels generated automatically from part reservation information improved traceability and part management.
4. The ERP system was adapted to associate standard parts and modules with customer projects by entering equipment BOM directly at the design stage.
5. The submission process was optimized using a method based on the analysis of data already in the ERP manufacturing costs. Submissions are now based on lists of pre-established modules, simplifying sales pricing.
6. In parallel with preparing the ERP for the modules, a methodology was adapted to carry out modular product design. This approach included steps such as sales analysis, the definition of technical specifications, concept development and design review. Some challenges were encountered in terms of the significant company resources that were required to make all the equipment offered by the company modular. Modular design and projects made possible by modularity such as parallel assembly, JIT and Kanban served as variables in the simulated experimental design plan.

7. Several essential prerequisites for Industry 4.0 implementation were validated and implemented. These included adopting lean principles and production agility, validating the presence of a high-speed Internet connection, validating real-time access to ERP data and developing strategic planning, all of which contribute to preparing the company to successfully integrate Industry 4.0.
8. Industry 4.0 technologies were also implemented, specifically data storage in a cloud-based solution, using Microsoft SharePoint, minimized use of paper-based information, improved accessibility and information management. SharePoint sites and Teams infrastructure were created to facilitate communication, document filing and project organization. These projects lead to the implementation of a paperless production floor, which was set as the last variable in the experimental design.
9. In parallel, several internal processes were automated to reduce repetitive tasks. These include sending drawings to suppliers, computerized document management for the finance and purchasing departments, creating work environments for customer projects and managing non-conformities with suppliers.

These projects have helped to improve company productivity, notably by improving engineering reaction times, reducing information or parts searches, facilitating document sharing and so on. These initial steps laid the foundation for adopting Industry 4.0 principles by implementing the most accessible technologies, such as a cloud-based solution and interconnections between systems already in place. The beginnings of a data culture were established. Opportunities to implement the use of cloud technology in the future were identified, such as managing production drawings, customer service documents and employee invoices that were still in a paper format. In conclusion, these implementations are an important step in the company's transformation to a more efficient, agile and future-oriented model, since they made it possible to structure the improvement process under project management and to begin the implementation of a culture of change.

In view of the time required to implement these projects, the rest of the strategy was evaluated using a business simulation to perform a plan of experiment. This blended approach aims to minimize the risks, time and costs associated with full implementation, making it possible to find the best solutions prior to enterprise deployment. The next section presents the experimental design, the dependent variable, the independent variables and the mathematical model.

3.4. Experimental Design

Three steps were involved in obtaining the experimental design results. The variables and levels are defined in Section 3.4.1 and regrouped in a model presented in Section 3.4.2. Then, a simulation replicating the company case is built in Sections 3.5 and 3.5.1 and validated in Section 3.5.2. The experimental design is then realized using a simulation in Section 4.

3.4.1. Variables and Levels

The variables were chosen from the adapted strategy and further validated through value chain mapping, an audit and alignment with the company's strategic plan created in Stage 1 to follow up on the case study.

Productivity was selected as the dependent variable for assessing the impact of the strategy on company performance aimed at transitioning to mass customization, measured according to the number of projects delivered per five-year production period. These variables directly serve the research objectives by evaluating the effectiveness and adaptability of the tailored Industry 4.0 strategy, using Industry 4.0 technologies as tools for achieving the company's shift toward mass customization. The strategy's effectiveness is proven by measuring the impact of the strategy's components on productivity. The success of the strategy's adaptability and flexibility in this specific business context is then demonstrated.

The independent variables in the experimental design are based on data already available within the company and on the previously conducted case study. Now that tools and an approach for designing modular products were prepared, the first variable is the use of modular design (B). The second variable is the use of JIT tools (A) to increase agility and create production batches, something that is now possible due to the use of modular products. Parallel product assembly (C) is possible due to a flexible layout in the form of dynamic cells. Implementing technologies at each workstation (D), with drawing displays and time collection, becomes feasible due to the prior establishment of cloud storage technologies in the company. Last, improvements are targeted by collecting, analyzing and creating KPIs based on the data collected and analyzed (E). All these projects lead the company toward a network enterprise concept while facilitating several projects using technological tools. These independent variables and their respective levels are presented in Table 1.

Table 1. List of variables and their levels.

Variable	Authors	Level 0	Level 1
JIT and Kanban (A)	[23]	Documents produced on request	Standard parts managed using the Kanban method
Modular Design (B)	[23,32,44]	Custom-designed and -manufactured products	Standard parts and module drawings used for 80% of equipment sold
Flexible Layout and Parallel Assembly (C)	[23,24]	Series equipment assembly	Parallel assembly of targeted equipment
Agile Information Systems—Intranet and Screens at Every Workstation (D)	[17,25,34]	Workers move to a common computer station to create their timecard and take part drawings	Computer station at each workstation to display drawings and for completing timecards
Performance Indicators, Continuous Improvement, Lean and Agility (E)	[40,45–47]	Current start-up times	SMED technique reduces bottleneck set-up times

The modifications to the simulation to operationalize the variables and thus obtain the results are explained below to provide a better understanding of the adjustments made to the simulation model.

Variable 1—JIT and Kanban (A)

The engineering team identified parts that could be standardized and managed using the Kanban method. At Level 1, parts are produced in batches for three months of use and managed in inventory by Kanban, permitting small-batch production and cutting the time required per part. At Level 0, parts are custom-made for each project, without being kept in inventory. Producing identical parts on the same work order reduces the average set-up time per part and is possible when creating modular products.

Variable 2—Modular Design (B)

The company intends to optimize its process by making 80% of its products modular with a similarity index greater than 0.45 (45%). To operationalize the modular design variable, when this variable is at Level 1, the design time is reduced by 90%, and the technical drawing time is reduced by 32% using standard models. These two values were obtained by comparing company data for two similar pieces of equipment, one modular and the other non-modular. The company's current design and drafting times were maintained when the variable was at Level 0. Modular design makes it easier to adapt to customer needs and possible to implement subsequent projects, such as pull production, guide and template creation and parallel module assembly.

Variable 3—Flexible Layout and Parallel Assembly (C)

The company's current production manager identified the sections of each piece of equipment that could be assembled in parallel. When the "Flexible Layout and Parallel Assembly" variable is at Level 1, the targeted equipment sections can be assembled in parallel, representing dynamic cells and a mixed assembly line. When the level is 0, all parts of the equipment must be assembled in a series, as they are in current production.

Variable 4—Agile Information Systems—Intranet and Screens at Every Workstation (D)

When the intranet and screens are available at each machining workstation, employee travel time to the time clock is reduced. At Level 1, this variable reduces set-up time by avoiding travel, thus simulating a computer station and intranet at each workstation to collect time and identify parts. The parts can then be moved by the on-duty clerk. At Level 0, the initial production time stays the same, including trips to the time clock and drawing searches.

Variable 5—Performance Indicators, Continuous Improvement, Lean and Agility (E)

This variable combines performance indicators, continuous improvement and lean and agility tools to target and improve plant productivity. Performance indicators, such as TRG components and the capacity load ratio, help target workstations for improvement. Lean tools support continuous improvement and increase the overall production capacity of the workstations targeted by the indicators. At Level 1, the workstations that limit production capacity are identified, and the gains from using the SMED technique are applied. The set-up time for the identified workstations is reduced according to the assessment of possible gains based on the company's data. Other improvements could have been evaluated for this variable. However, the proposed improvement takes into account the resources available to an SME in the early stages of implementing a change process. At Level 0, the initial set-up times are retained.

Following the explanation of the variables, the corresponding research hypotheses are as follows:

Hypothesis 1: *Implementing a JIT approach through the establishment of Kanban for standard parts enhances the company's performance.*

Hypothesis 2: *The modular design of best-selling products contributes to the successful implementation of Industry 4.0.*

Hypothesis 3: *A flexible production layout allowing the parallel assembly of different equipment parts enhances the company's performance.*

Hypothesis 4: *An intranet with a screen at each workstation reduces worker movement in machining, leading to enhanced company performance.*

Hypothesis 5: *Implementing performance indicators to target the factory bottleneck, combined with the use of continuous improvement and lean tools on this workstation, improves the company's performance.*

3.4.2. Model Description

The mathematical model evaluated is as follows:

$$Y_{ijkL} = \mu + A_i + B_j + C_k + D_l + E_m + AB_{ij} + AD_{il} + BD_{jl} + BE_{jm} + \varepsilon_{ijklm} \quad (1)$$

where

μ: Average of measured responses;

A_i: Variation caused by level i of the "JIT and Kanban" variable;

B_j: Variation caused by level j of the "Modular Design" variable;

C_k: Variation caused by level k of the "Flexible Layout and Parallel Assembly" variable;

D_l: Variation caused by level l of the "Agile Information Systems—Intranet and Screens at Each Workstation" variable;

E_m: Variation caused by level m of the "Performance Indicators, Continuous Improvement, Lean and Agility" variable;

AB_{ij}: Variation caused by the interaction between level i of the "JIT and Kanban" variable and level j of the "Modular Design" variable;

AD_{il}: Variation caused by the interaction between level i of the "JIT and Kanban" variable and level l of the "Agile Information Systems—Intranet and Screens at Each Workstation" variable;

BD_{jl}: Variation caused by the interaction between level j of the "Modular Design" variable and level l of the "Agile Information Systems—Intranet and Screens at Each Workstation" variable;

BE_{jm}: Variation caused by the interaction between level j of the "Modular Design" variable and level l of the "Performance Indicators, Continuous Improvement, Lean and Agility" variable;

$\varepsilon_{o(ijklm)}$: Experimental error;

Y_{ijklm}: Measured response (number of projects delivered per five-year production period).

Interactions were selected based on discussions with company experts. The interactions studied concern equipment modularization and the intranet at each production workstation. Interactions AB (JIT and Kanban and Modular Design) and BE (Modular Design and Performance Indicators, Continuous Improvement, Lean and Agility) were chosen since the design and drafting department is the current bottleneck in the plant. Combining any variable with the "Modular Design" variable therefore has a greater effect than the variable alone. Interactions AD (JIT and Kanban and Agile Information Systems—Intranet and Screens at Each Workstation) and BD (Agile Information Systems—Intranet and Screens at Each Workstation and Modular Design) were chosen since they represent the main effects of implementing the first Industry 4.0 technologies in manufacturing SMEs.

To meet the needs of the study, an orthogonal Taguchi L16 experimental design was chosen, corresponding to the number of parameters and levels because orthogonal plans guarantee a balance in the impact of each variable, thus providing a reduced yet efficient experimental design. This ensures that each experiment is evenly represented for each variable. The Taguchi method is widely accepted in the scientific community for its ability to yield reliable results in a shorter timeframe. The chosen design allows us to study five variables at two levels, as well as the four targeted interactions. Error is minimized due to a sufficient number of degrees of freedom remaining for error when considering those necessary for variable and interaction analysis. The sixteen experiments were replicated five times to increase reliability.

The next section presents the design, preparation and validation of the simulation replicating the business case in order to collect the results of the experimental design. The simulation is used to assess the company's productivity increase and thus justify whether to implement these projects.

3.5. Simulation

The simulation was conducted with Simio, chosen for its built-in experimental design functionality and because licenses were already held that met the project's specific needs.

The simulation model starts with creating seven projects, which represent a demand for equipment production to fill the system, or the average number of projects in progress in the company. Each project is assigned a project number, a priority and a number of pieces of equipment. The number and proportions of equipment sales vary according to the company's historical data (2018 to 2021) and are presented in Table 2.

Once the project is created, project and equipment design begin. The resources available for each workstation are selected according to skills and assigned a task according to priority. The task is then carried out according to the company's historical times. The same process applies to the drawing station. Once completed, the equipment drawing is printed and sent to the assembly station.

The equipment is then divided into a set of parts required for its assembly. Each part has a priority identical to that of the associated piece of equipment and follows a specific path according to the established routing, historical production times and required BOM. Once the routing is complete, the part is placed in inventory or reserved for the project section.

Table 2. Pareto analysis of equipment for a palletizing project.

Equipment Name	Quantity	Percentage
Chain conveyor	11	16.2%
Belt conveyor	9	13.2%
Gripper	7	10.3%
Safety perimeter	7	10.3%
Pallet magazine	7	10.3%
Robot	7	10.3%
Cardboard warehouse	5	7.4%
Conveyor scale	3	4.4%
Gravity conveyor	3	4.4%
Leveling conveyor	3	4.4%
Bagging machine	2	2.9%
Wrapper	2	2.9%
Gripper conveyor	1	1.5%
Bagger	1	1.5%
Total	68	100.0%

The electrical panel is assembled in parallel with the parts and equipment production.

When all equipment parts are complete, they are deducted from inventory according to BOM quantities, and the equipment becomes available for assembly. Assembled equipment is held until all project equipment has been assembled before being grouped together for delivery.

To maintain a constant flow and represent the company's situation, the simulation assumes that a new order is launched as soon as a project is delivered, meaning that there are always seven projects running in the simulation. Figure 4 shows the visual representation of the simulation in Simio.

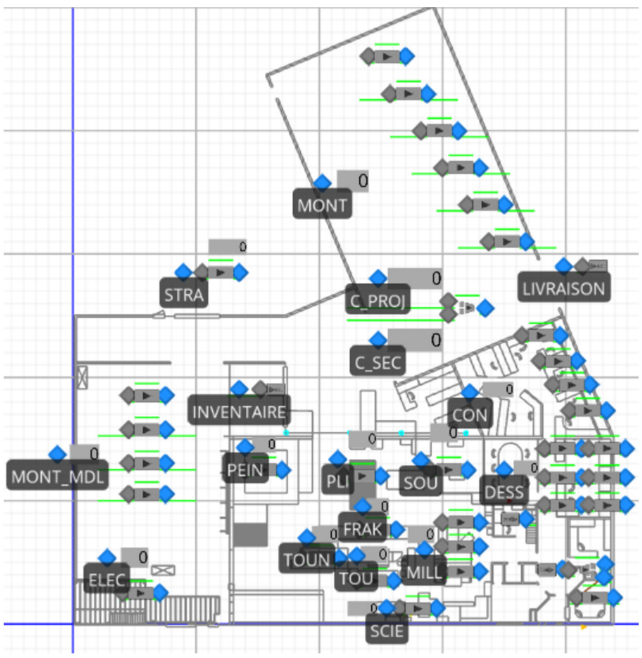


Figure 4. Simio version 14 simulation software representation.

3.5.1. Simulation Data

Since the company manufactures customized equipment, it is difficult to obtain a distribution of manufacturing times for each part. The simulation uses the production times of a typical project for each piece of equipment. A generalized distribution for all parts was determined based on the production manager's experience and historical data of parts produced on several occasions. The production times entered in the simulation correspond to a triangular distribution with a minimum bound at 70% of the part's historical production time, a median time at the historical production time and a maximum bound at 130% of this same time.

The simulation assumes that the triangular distribution parameters for production times, the specific times for project-selected parts and the constant number of seven ongoing projects are fully representative of the company's actual operational situation.

3.5.2. Simulation Validation and Steady-State Evaluation

Warm-up time was assessed by plotting project delivery times over a period of five working years, equivalent to 8887.5 h. A reduction in variation was observed after 2.363 working years, or 4200 h.

To reduce the impact of producing one more or one less project during the year, the simulation duration was set at five years. This reduces the impact of results variations caused by the low number of projects completed per year.

Several validations were conducted during simulation creation to ensure the results were valid. These included a visual validation of parts, equipment and operator flow; average value-added time; inventory values; number of projects in the system; production times; and BOM structure. Once the simulation was complete, performance indicators were compared with those of the company to validate the model, including the number of projects delivered annually and the utilization rate of workstations and workers.

Once the simulation model was designed and validated, it was used to carry out the experimental design according to the established independent variable levels. The experimental design results and analysis are presented in the following section.

4. Experimental Design Results and Analysis

4.1. Experimental Results

Once the simulation was created and validated, the experiments were conducted by adjusting the simulation parameters according to the variable levels in the defined Taguchi L16 design. The results of the experimental design were compiled and are presented in Table 3.

Table 3. Taguchi L16 experimental design results in number of projects delivered.

N°	Taguchi Plan Column					Results					
	A	B	C	D	E	Number of Projects Delivered per 5 Years of Production					
	JIT and Kanban	Modular Design	Flexible Layout and Parallel Assembly	Agile Information Systems	Performance Indicators, Continuous Improvement, Lean and Agility	Ans.1	Ans.2	Ans.3	Ans.4	Rep.5	Avg.
1	0	0	0	0	0	60	61	60	64	61	61.2
2	0	0	0	1	1	70	71	67	73	69	70
3	0	0	1	0	1	67	70	69	69	69	68.8
4	0	0	1	1	0	64	63	67	65	63	64.4
5	0	1	0	0	1	72	72	70	71	72	71.4
6	0	1	0	1	0	65	65	65	65	66	65.2
7	0	1	1	0	0	62	58	65	64	59	61.6
8	0	1	1	1	1	77	77	74	76	78	76.4
9	1	0	0	0	1	69	66	67	67	65	66.8
10	1	0	0	1	0	71	72	67	68	71	69.8
11	1	0	1	0	0	69	68	68	71	69	69
12	1	0	1	1	1	68	68	70	66	66	67.6
13	1	1	0	0	0	72	74	74	74	72	73.2
14	1	1	0	1	1	84	80	82	78	82	81.2
15	1	1	1	0	1	81	78	81	80	77	79.4
16	1	1	1	1	0	73	75	77	75	75	75

The residual values graph verified that the residuals were normally distributed. Main effects and variance analyses were then performed following this validation.

4.2. Table of Main Effects

Figure 5 shows the average results for each of the five main variables by level. This graph shows the effect of the independent variables on the dependent variable. Although the Flexible Layout and Parallel Assembly (C) variable shows a weaker impact, it is still positive. All other variables show a strong positive impact, especially A, B and E.

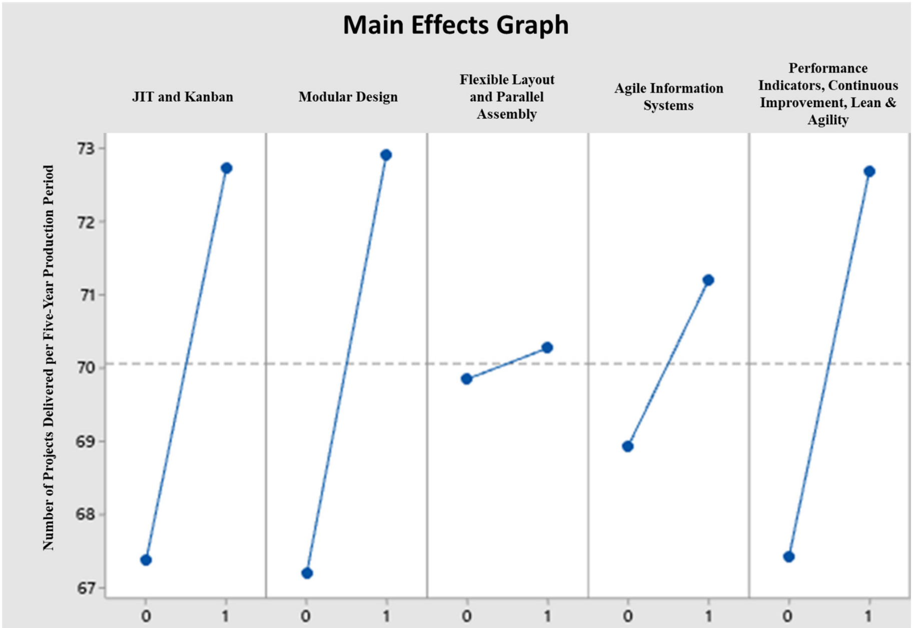


Figure 5. Graphical results of the impact of each independent variable.

Figure 6a shows the effect of the interaction of the Modular Design and JIT and Kanban (AB) variables on the number of projects delivered. Both Modular Design (B) and JIT and Kanban (A) have a positive impact on the dependent variable. However, when these variables are combined, they have a greater impact than the sum of their individual impacts.

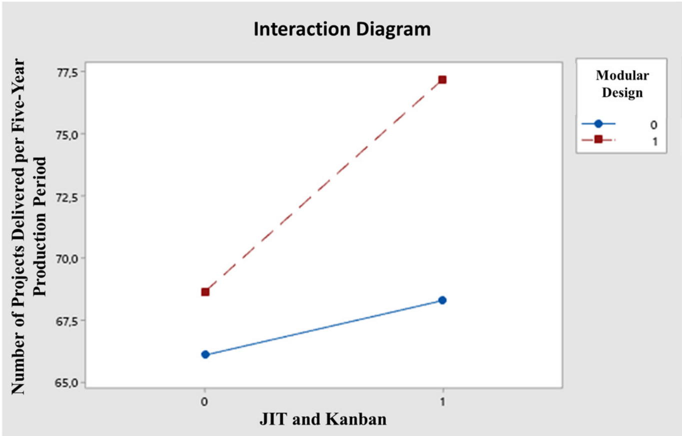
Figure 6b shows the effect of the interaction between Modular Design and the Performance Indicators, Continuous Improvement, Lean and Agility (AE) variable. The lines in this figure are very similar to those in the previous figure. These two variables combined also have a greater impact than the sum of their individual impacts.

4.3. Analysis of Variance

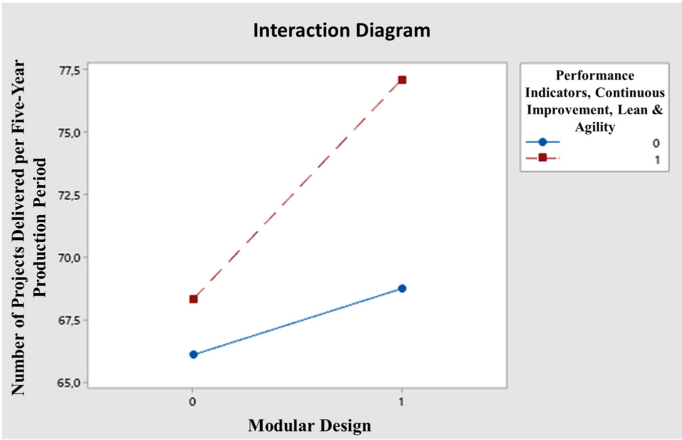
Table 4 presents an analysis of variance (ANOVA) of the general linear model of the experimental design results. The analysis was performed with Minitab version 21 software. The confidence level was set at 95% for the analysis ($\alpha = 5\%$). This means that a significant variable must have a *p*-value less than or equal to a significance level of 0.05. A variable with a *p*-value greater than 0.05 is non-significant.

In terms of their effect on the number of projects delivered, the most significant variables are ranked as follows: Modular Design (B), JIT and Kanban (A), Performance Indicators, Continuous Improvement, Lean and Agility (E) and Agile Information Systems (D). These four independent variables have an impact on the number of projects delivered per period, validating hypothesis 1, 2, 4 and 5. The Flexible Layout and Parallel Assembly variable is not significant but still shows an upward trend in the number of projects delivered according to the main effects graph.

The interactions between Modular Design and Performance Indicators, Continuous Improvement, Lean and Agility (BE), as well as JIT and Kanban and Modular Design (AB), are significant according to the ANOVA analysis.



(a)



(b)

Figure 6. (**a**) Diagram of the interaction between Modular Design and JIT and Kanban. (**b**) Diagram of the interaction between Modular Design and Performance Indicators, Continuous Improvement, Lean and Agility.

Table 4. Analysis of variance (ANOVA) of the general linear model.

Source	Degree of Freedom	Sum of Fitted Squares	Adjusted Mean Square	F Value	*p*-Value
JIT and Kanban (A)	1	577.81	577.812	93.20	0.000
Modular Design (B)	1	655.51	655.512	105.73	0.000
Flexible Layout and Parallel Assembly (C)	1	3.61	3.613	0.58	0.448
Agile Information Systems (D)	1	103.51	103.513	16.70	0.000
Performance Indicators, Continuous Improvement, Lean and Agility (E)	1	556.51	556.513	89.77	0.000
JIT and Kanban × Modular Design (AB)	1	201.61	201.613	32.52	0.000
JIT and KANBAN × Agile Information Systems (AD)	1	19.01	19.013	3.07	0.084
Modular Design × Agile Information Systems (BD)	1	12.01	12.013	1.94	0.168
Modular Design × Performance Indicators, Continuous Improvement, Lean and Agility (BE)	1	189.11	189.112	30.50	0.000
Error	70	433.98	6.200		
Inadequate adjustment	6	245.18	40.863	13.85	0.000
Pure error	64	188.80	2.950		
Total	79	2752.69			

5. Discussion and Suggestions

As part of this research, an Industry 4.0 implementation strategy was adapted to a company producing robotized packaging systems. The principles of agility and lean had a positive impact on the company's performance, justifying their integration into the adapted strategy. The initial stages of the approach were successfully implemented in the company. Adopting the first practices of Industry 4.0, notably cloud storage and systems interconnectivity, proved to be an important lever in the company's transformation process, resulting in the first steps toward a culture of change, data and improvement. Finally, a simulation was used to measure the impact of proposed solutions and evaluate the impact of the latest projects within the strategy.

5.1. Company Case Analysis

This case study illustrates the performance improvements achieved by adapting an Industry 4.0 implementation strategy. Several changes were implemented, such as the use of data already present in the ERP system, modular product design, modular design management in the ERP, cloud storage and implementing automated processes. In response to the company's need to implement and search for existing modules, codification for part and module use was proposed and implemented. A structured approach to modular product design integrating product design and agility steps was adapted and implemented for the first products.

The company's implementation of each step led to the following gains:

- A 40% reduction in time spent searching for information and parts in the assembly department;
- A 50% reduction in the number of surplus standard parts produced over a six-month period;
- A 90% reduction in product design time and a 32% reduction in drawing time using standard modules and parts;
- A 4.4% reduction in the number of standard parts following the elimination of duplicates;
- The realization from management that a select group of options corresponds to 80% of the options sold;
- The understanding that ordering five or more identical parts from a supplier reduces the unit purchase cost by 20% compared with buying one part;
- A reduction in the number of paper documents, as well as in the search, filing and transcription of these documents;
- Easier sharing of information and documents between internal workers and with external suppliers;
- Reduced risk of data and document loss following the implementation of cybersecurity solutions;
- A marked improvement in document tracking, with the introduction of statuses and tracking lists;
- Reduced repetitive tasks such as implementing Teams, authorizing SharePoint access and drawing searches.

Implementing the first stages of the strategy in the company resulted in significant gains, mainly in product design, an important stage of Industry 4.0. These results are further generalized in Section 5.5, suggesting their potential applicability to other contexts. The company's overall results help demonstrate that Industry 4.0 and agility are long-term investments, as argued in the literature [48].

The company experienced a decline in performance, corresponding to the trough of the change curve. This is normal, given that many new features were implemented. The company case demonstrates that a company needs time to be ready to move toward mass customization and Industry 4.0.

A strategic plan and meetings with external advisors have moved the company forward on the road to strategy implementation. The strategic plan seems to have had a significant impact on management motivation and the amount of action taken to improve the company, illustrating the effectiveness of the adapted strategy.

The acceptance of change, stimulated by a clear strategy and vision, the availability of human resources and the presence of management leadership remain a challenge. These challenges are signs that the company still needs time to get ready to pursue the strategy. The support provided during the case study accelerated the company's progress and helped resources achieve change acceptance.

5.2. Next Steps Analysis

The simulation was used to evaluate the strategic projects to be implemented later in the company. In particular, variables A, B, D and E emerged as significant following the analysis of variance. A JIT approach, Kanban (A), modular design (B), agile information systems (D) and the introduction of performance indicators to improve the bottleneck of workstations using a lean and agile approach (E) can increase the organization's performance. The company must therefore continue to implement these significant variables to improve its performance. Variable C could not be confirmed and requires further research to verify the conditions for success.

Modular products, followed by Kanban, small production batches and lean bottleneck improvements, should be implemented in the order presented. Access to a computer system with the company's intranet at each workstation could follow the implementation of the other solutions at a later stage. Implementing these variables could increase the number of projects delivered per year by 32.7%.

The simulation results, including the predicted effectiveness of these key variables, underline the effectiveness of the strategy adopted. The research demonstrates the importance of performing a simulation in order to prioritize the next steps and thus validate that a gain exists before implementing solutions. The results allow us to validate and prioritize the implementation of the chosen solutions in the company, taking into account performance improvements and project precedence.

5.3. Strategy Demonstration

The company is currently engaged in a modular design process, which will make it easier to have modules produced by external suppliers to increase production capacity. This orientation toward the network enterprise concept will subsequently lead the company to further improve system interconnectivity, the quality of parts produced, production planning and the implementation of performance indicators for all aspects of the business.

To manage risks such as disconnected technologies, poor communication and low worker involvement, the company has expanded its information technology and continuous improvement teams. Focus groups that include workers on specific issues and projects have been established to enhance leadership and internal communication. Additional technologies for online part sales or automating certain business processes are envisaged for the future.

5.4. Global Analysis—Technologies

The study results support the idea that projects like modular design and improved business agility, which serve to prepare companies for implementing more advanced technologies, have a significant impact on company productivity. This enables the company to implement a mass customization strategy more quickly and at lower cost, since implementing advanced technologies can be costly and complex.

Effort-wise, implementing modular design required a high level of internal resources but opened the door for greater gains and future projects. Adopting simple Industry 4.0 technologies required medium internal effort, and integrating advanced business agility practices required low internal effort. Importantly, all these solutions required minimal external costs.

The company achieved significant efficiency gains by implementing modular product design. A case study by Abdulnour et al. [12] showed a 36.6% productivity increase, and our case study company attained a 32.7% gain, aligning closely with other cases. By implementing these practices before adopting advanced Industry 4.0 practices, the company is prepared to integrate technologies and use them more effectively to offer customized products on a large scale.

The company case study demonstrates that a change of this scale requires time to be ready for the shift to mass customization and Industry 4.0. This is further evidence that a preparation strategy and prerequisites are needed before implementing more advanced technologies.

5.5. Global Analysis—Strategy Adaptability

In the company case study, the adapted strategy led to significant organizational performance improvements. Similarly, the improvements and technologies tested in the simulation positively impacted productivity. These significant positive impacts confirm that the strategy was successfully adapted for this SME, meaning that the basic strategy is adaptable and flexible and could potentially be applicable to the specific needs of other companies.

The results demonstrate the successful adaptation of the Industry 4.0 implementation strategy for a company specializing in robotic packaging systems, characterized by a varied product range and more than 30 types of customized equipment. The results obtained closely align with those obtained by Abdulnour et al. [12] when adapting the same strategy. A similar strategy was also implemented by Abdulnour et al. with positive results in line with those obtained. The study also confirms the findings of Bouchard et al. [11], suggesting similar strategy applicability and effectiveness. This specific case raises additional challenges compared with previous studies, particularly in view of the great complexity of customer product dimensions, weights and specifications. Despite the complexity and variety of the products, the results of this study demonstrate the flexibility and adaptability of this approach in complex industrial environments.

A number of factors were neglected, limiting the results of this study, such as quality, maintenance, limitation to a single product range, market dynamic, the feasible implementation of chosen technologies or tools in a company and an acceptable implementation threshold for prerequisites. This study presents only one company case and requires further examples of successful strategy adaptations and implementations before it can be generalized to several company sizes and business sectors.

Future research could deepen modularity management approaches and tools for products by creating modular and reconfigurable automation, market and process levels. An adaptive strategy could be developed through action research, focusing on adapting existing modularity tools in the Industry 4.0 context. Improved modular product management could facilitate the implementation of the network enterprise concept through partnerships with multi-level suppliers. The exploration of how organizational factors interact with technological and strategic elements in the application of Industry 4.0 also remains a promising direction for future research. These research orientations contribute to developing solutions adapted to SMEs to reinforce their competitiveness in the era of mass customization in the context of Industry 4.0.

The transition to the Industry 4.0 strategy in this company required a cultural change, facilitated by employee involvement, worker idea contribution, workgroups and increased managerial trust. This approach not only led to significant solution acceptance but is also currently being pursued and appreciated by both management and workers due to the marked improvements. This study confirms the importance of these factors in reducing resistance to change and ensuring the strategy's success. In the study by Bouchard et al. [11], the first change process was carried out several years before the strategy was implemented. In the case at hand, the company initiated the strategy as a first step. This time difference between the studies highlights the specific contexts of each company. This study underlines the need for cultural change and acceptance of solutions and confirms the importance of considering the factors and specificities of each company, as well as the prerequisites for Industry 4.0, when adapting a strategy.

Companies must therefore prioritize implementing a readiness strategy including agility, modular design, prerequisites and core technologies before adopting more advanced technologies. This strategy of implementing small projects freed up the time of several resources dedicated to implementing improvement projects for the future. The success of the implementation underscores the importance of prerequisites in an Industry 4.0 strategy, a process where Digital Innovation Hubs (DIHs) can serve as valuable intermediaries [49]. By offering resources, expertise and networking opportunities, DIHs can assist companies in identifying and implementing these prerequisites more effectively [50].

6. Conclusions

This in-company action research study on implementing Industry 4.0 in SMEs meets the need stated by several authors [8–10] for in-company case studies. This study is part of a broader research project that aims to adapt Industry 4.0 strategies to SMEs in different sectors based on the concepts of lean, agility and modular design [11,12]. This study further advances preliminary work in Industry 4.0 by offering SMEs a comprehensive strategy that increases the success rate of Industry 4.0 implementation. It emphasizes the importance of preparatory steps, challenging the current subsidy focus on technology alone, which has led to implementation failures for many businesses.

The context was specialization in robotic systems, product complexity and variety and a shift from engineering-to-order to assemble-to-order. A strategy was adapted from the literature, defining the objectives, tools and practices to be implemented; the implementation sequence; and the implementation stages. Implementation of the strategy yielded multiple gains, including a 40% time reduction in searching for parts, a 50% reduction in surplus parts and a reduction in design and drawing time by 90% and 32%, respectively, thus improving the company's performance. The significant organizational performance improvements in the case study and in the experimental design suggest that the adapted strategy is effective, flexible and can be adapted to different contexts by adjusting the technologies and projects implemented. Adapting the strategy to a company's specific context is essential. This article is further proof that each company needs to be assessed individually to successfully adapt the Industry 4.0 implementation strategy to its specific needs, as was performed in this successful case study.

Further research adapting tools and projects using the same strategy approach in other fields of activity is needed in order to generalize a strategy adaptation approach to a wider field. A research opportunity also lies in examining the effects of strong SME leadership combined with the strategy developed to accelerate SME transformation.

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