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Six-Sigma Reference Model for Industry 4.0 Implementations in Textile SMEs

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Abstract: The textile and apparel industry is a major contributor to Latin American economies. However, in these economies the industry is characterized by limited technological infrastructure, which has led to inefficient performance and the significant generation of water, material, and product waste through its supply chain (SC). Currently, Industry 4.0 has led to important benefits in manufacturing industries, but its application in the textile field has been limited to few case studies. The present work expands on this aspect with a critical review of Industry 4.0 concepts and principles, and our main contribution consists of an implementation guideline model. The model was based on Six Sigma and the Rothwell and Zegveld model for continuous improvement and innovation projects in manufacturing and business enterprises. In each step, key aspects such as the specific skills of the interdisciplinary team, assessment tools, and implementation/prototyping tools are highlighted. A discussion of a case study is presented to support the applicability of the model for Industry 4.0 pilot projects.

Keywords: textile industry; Industry 4.0; sustainability; implementation guidelines; SMEs

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1. Introduction

Industry 4.0 (I4.0) involves the digital transformation and the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data (BD) analytics, augmented/virtual reality (A/VR), smart sensors, simulation, cybersecurity, cloud computing, and robotics to improve productivity, efficiency, flexibility, and connectivity in manufacturing and industrial processes [1]. The specific outcomes of this integration are efficient real-time data exchange and predictive maintenance, decentralized decision making, the fast customization of products and services, cyber-physical systems (CPSs), additive and cloud manufacturing, "digital twins", smart factories, and industrial IoT [2,3]. Thus, I4.0 can be defined as the "digitalization of the manufacturing sector, with embedded sensors in virtually all product components and manufacturing equipment, ubiquitous CPSs, and analysis of relevant data" [4]. Note that "digitalization" refers to the use of digital technologies to improve business operations and create new value for customers, while "digitization" refers to the process of converting physical information into digital formats.

While I4.0 has been mainly studied and applied within the manufacturing sector (i.e., Manufacturing 4.0), the following sectors are also studying and developing I4.0 technologies [5,6]:

- *Automotive*: for the enhancement of smart production lines, connected vehicles, autonomous driving, predictive maintenance, and customized production.
- *Energy and utilities*: for the optimization of energy management and grid efficiency, renewable energy integration, and smart metering implementation.
- *Healthcare*: for the improvement and implementation of telemedicine, electronic health records, AI-powered diagnostics, remote patient monitoring, and smart medical devices.

- *Logistics and supply chain (SC)*: for the improvement of inventory management, warehouse automation, real-time tracking, predictive analytics, and autonomous vehicles.
- *Agriculture*: for the implementation of sensor-based monitoring, drones, robotics, AI-powered analytics, and yield prediction.

Within the manufacturing sector, the textile industry is a major contributor to environmental pollution worldwide [7]. Regarding waste generation, the textile industry requires huge amounts of water and chemicals throughout all production stages (i.e., raw material extraction, spinning, knitting, and dyeing). Although in Europe 2–10% of the environmental impact is associated with the clothes industry [8], the impact is more significant in developing countries, where most textile companies are located [9]. In this regard, I4.0 can support sustainable efforts to reduce the environmental impact in these countries and also improve their industry performance [10]. Recently, the term "Apparel 4.0" has been coined to address I4.0 within the fashion industry, which is directly associated with the textile industry, identifying benefits such as better agility; transparency; increased quality, productivity, and customer satisfaction; and reduced operational costs and delivery time [11,12].

In this case, I4.0 technologies can support valuable processes to improve the sustainable aspects of the textile SC. However, as the textile industry involves the continuous flow of capital, materials, chemicals, processing machinery, and finished products, it faces different challenges for I4.0 implementation. Among these, the following can be mentioned [13,14]:

- Significant investment costs: I4.0 technologies require investments in infrastructure, equipment, and training. Particularly, small and medium-sized enterprises (SMEs) may face financial constraints when adopting these technologies.
- Lack of trained staff: I4.0 technologies demand a skilled workforce proficient in data analytics, IoT, automation, and digital systems.
- Outdated or limited technology: In emerging economies and SMEs, the textile industry often relies on outdated machinery and systems that may not be compatible with newer I4.0 technologies.
- Limited SC integration: I4.0 promotes end-to-end connectivity and collaboration within the SC. However, this is a technologically complex task due to varying technological capabilities and interoperability between the different SC stakeholders such as suppliers, manufacturers, and retailers.
- Limited or no scalability and flexibility: Although I4.0 enables agility and flexibility in manufacturing processes, scaling these solutions across different production lines and factories can be a logistical and operational challenge.
- Lack of data management and security systems: With increased connectivity and data generation, few SMEs realize and procure effective systems to manage and secure large volumes of data. Cybersecurity threats and data privacy concerns must be addressed to ensure the protection of sensitive information.
- Compliance with regulations and standards: Current textile regulations and standards must ensure the safe, efficient, and ethical use of emerging I4.0 technologies.

Mexico is an emerging economy, and the textile industry is a major contributor to its gross domestic product (GDP). Globally, Mexican exports of textile products have continuously declined since the year 2000, which has severely affected its competitiveness. In this regard, the improvement of productivity, quality, and innovation have been identified as factors that are directly and positively correlated with the competitiveness of companies in the textile and clothing industry [15].

However, in practice, most SMEs claim that I4.0 implementations have drawbacks, such as the absence of a clear roadmap or guidelines, financial uncertainties, a lack of knowledge about new concepts, and a lack of skilled employees [12]. Hence, in this work a conceptual model regarding I4.0 for Mexican SMEs is presented to provide reference guidelines regarding the critical stages for I4.0 projects. A key aspect of this model is the integration of a sustainable approach to improve competitiveness within the textile sector.

The advances of the present work start in Section 2 with a review of key aspects of I4.0, such as definitions of IIoT/IoT, CPSs, smart factories/products, vertical/horizontal integration, and the importance of maturity models (MMs) and design principles (DPs). Because the textile industry is a major contributor to environmental pollution worldwide, Section 3 presents an analysis regarding the pertinence of I4.0 for sustainability and waste reduction purposes. Then, the proposed implementation plan, which was based on Six-Sigma (an established continuous improvement methodology for manufacturing processes) and the MR&Z model (for innovation) is described in Section 4. The description of this plan includes recommendations regarding IIoT/cloud computing/prototyping software tools that are crucial for I4.0 pilot projects. The description of the implementation plan is complemented by a discussion regarding its applicability with a case study in Section 5. Finally, the conclusions and future work are presented in Section 6.

2. Understanding Key Aspects of I4.0

To propose a guideline I4.0 model, it is important to understand the differences when considering current production systems. The first industrial revolution (I1.0) refers to the technological transition period between the years 1760 and 1900, when the steam engine (hydropower) and coal-powered machines were invented. During the second industrial revolution (I2.0), which took place between the years 1900 and 1960, the invention of the internal combustion engine and electricity led to rapid industrialization and mass production (assembly lines) [16]. Between the years 1960 and 2000, the third industrial revolution (I3.0) further accelerated automation using electronics and information technology [17]. The fourth industrial revolution (I4.0), which started in 2000, has expanded upon I3.0 with the development of CPSs and smart factories, integrating all smart technologies, such as additive manufacturing (3D printing), IoT, cooperative robots, BD, AI, and A/VR. Digitalization is a key feature for the implementation of I4.0.

This is the reason why manufacturing systems that have extensive automated processes and sensors are not considered as I4.0 systems, even though they are clear examples of I3.0 systems. I4.0 "envisages an environment whereby smart machines can communicate with one another, not only to enable the automation of production lines but also to analyze and understand a certain level of production issues and, with minimal human involvement, to solve them" [1]. I4.0 requires that human-to-human, human-to-machine, machine-to-machine, and/or service-to-service interconnections are enabled to achieve complete horizontal, vertical, and end-to-end integration [17]. Within the I4.0 context, these integration schemes establish how the different elements (systems, processes, technologies, and products) within the manufacturing or industrial environment must be interconnected and collaborate with each other.

Knowing these specific differences in concepts is important to define reference guidelines for evolving I3.0 systems to I4.0 systems [17]. Table 1 presents a comparative review and description of the most common terms used in the I4.0 literature, while Table 2 describes the managerial aspects of the horizontal, vertical, and end-to-end integration of I4.0 technologies. Table 3 presents a review of the design principles (DPs) of I4.0, which are guiding concepts that drive its implementation. As such, these principles aim to:

- Reduce the knowledge gap for implementing I4.0 technologies and propose means to systematize them [18,19];
- Accomplish real-time connection between the physical and virtual worlds (virtualization) [20];
- Allow I4.0 system and application professionals to develop and implement successful and sustainable I4.0 systems [21].

Thus, they involve key ideas and features that must be considered while designing, implementing, and developing I4.0 projects. They also serve as the basis for skill and continuous training planning.

Table 1. Differences between common terms and features in the I4.0 literature.

Term	Description
Smart factory	Also known as a "digital factory" or "factory of the future", this term refers to a highly automated and interconnected manufacturing facility that leverages advanced technologies and data-driven systems to optimize operations, improve productivity, and enhance flexibility. As such, it is a concept within the framework of I4.0 and encompasses the entire manufacturing facility, including equipment, processes, and systems [22,23].
CPS	This refers to a system that combines physical components with computational and communication capabilities, enabling interaction and integration between the physical and digital worlds. Hence, a CPS integrates physical processes (i.e., sensors, actuators, and control systems) with computer systems, networks, and software [17]. While in practice a smart factory is frequently considered as equivalent to a CPS, the smart factory is a specific implementation or realization of a CPS within the manufacturing domain [23]. In contrast, a CPS can be applied to various domains, including transportation, healthcare, and energy systems [17]. Both have the following key features: high interconnection and flexibility, dynamic reconfiguration through self-organization, self-learning and self-adaptation, and deep integration [23].
Smart products	These are physical products that have embedded technology, connectivity, and data-processing capabilities, enabling them to gather and exchange data, interact with users or other devices, and provide enhanced functionality and user experiences [24]. IoT is the main technology to achieve connectivity and intelligence for these products.
Internet of Things (IoT)	This is the fundamental element of I4.0, and it consists of sets of interconnected static and/or mobile devices equipped with communication, sensors, and actuator modules connected through the Internet [25].
Industrial IoT (IIoT)	This is the application of IoT to a CPS to produce intelligent manufacturing goods and establish smart factories [25,26].
Smart/intelligent production	This system is characterized by its cognitive ability to perform efficient interaction and collaboration between humans and artificial entities (i.e., software, machines, and products) throughout complex processes across the entire value-creation chain [27]. While the smart factory is a tangible implementation of advanced manufacturing concepts, intelligent production refers to the smart capabilities and strategies applied within the production process of the smart factory. Intelligent production is focused on optimizing production planning, scheduling, quality control, and decision making throughout the production life cycle.
Digital twin	This represents a virtual replica or representation of a physical object, system, or process. It is created by integrating real-time data from the physical counterpart with digital models, simulations, and analytics. Its purpose is to enable the monitoring, analysis, and optimization of the physical system by providing a digital representation that can simulate and predict its behavior [28]. While both digital twins and CPSs involve the integration of physical and digital components, digital twins focus on creating virtual replicas to monitor and optimize the behavior of physical systems. In contrast, CPSs are systems wherein physical processes and digital capabilities are tightly integrated to enable real-time interactions and control.

Table 2. Description of the integration aspects of I4.0 technologies.

Type	Description
Horizontal integration (HI)	This is the integration and connection of different processes and functions at the same hierarchical level within a company, or across complementary or similar companies in a SC [29]. Examples of HI are cross-departmental integration (communication and data sharing between different departments within a company, such as R&D, production, marketing, and sales); supplier–customer integration (lateral collaboration with suppliers and customers to exchange data, forecasts, and production plans); and the interoperability of systems (efficient communication between software and devices across all different processes). The integration requires careful planning, effective communication, cultural alignment, regulatory compliance, and the management of organizational change [30]. As benefits of HI, the following can be mentioned: enhanced collaboration and synergies, improved operational efficiency and innovation capabilities, access to new markets or customer segments, and the ability to provide end-to-end solutions.
Vertical integration (VI)	This is the integration and connection of systems and processes between different stages or hierarchical levels within a company [29]. This involves expanding control or ownership over multiple stages of the value chain, from raw material acquisition to the delivery of the final product to the end customer, and the digitalization and standardization of internal processes and data flows [30]. Examples of VI are shop floor integration (the connection of machines, sensors, and control systems on the shop floor to gather real-time data about production processes and resource performance); operational integration (manufacturing execution systems (MESs) and enterprise resource planning (ERP) systems are integrated to perform efficient production schedules based on real-time data); SC and customer integration (suppliers and logistics partners are integrated to monitor and manage the flow of raw materials and finished products throughout the SC, and customers are managed through customer relationship management (CRM) systems to better understand customer demand changes). It also requires careful planning, investment in technology and infrastructure, and the effective management of complex inter-dependencies between the value chain stages. As benefits of VI, the following can be mentioned: increased operational efficiency, reduced lead times, improved product quality, enhanced customer experience, and better control over the value chain.

Table 2. *Cont.*

Type	Description
End-to-end integration (EEI)	This involves the integration and connectivity of all stages and entities of the value chain, from product design to final product delivery, from suppliers to customers, using advanced digital technologies and data-driven systems. This integration of processes, systems, and data across the entire life cycle of a product or service enables real-time information exchange, improved visibility, and enhanced collaboration with different companies and customers [29]. Examples of EEI systems are digital threads (the creation of a digital representation of a product and its production process, which can be accessed and updated throughout the product's life cycle); digital twins (providing virtual models of physical assets and products to perform real-time monitoring, predictive maintenance, and the assessment of different scenarios); and collaborative design (the creation of cross-functional teams for product design considering current and future manufacturing and SC constraints). EEI requires careful planning, investment in advanced technologies, standardization, and data security measures. As benefits of EEI, the following can be mentioned: increased operational efficiency, reduced costs, enhanced product quality, increased agility, better customer satisfaction, and faster responses to market changes.

Table 3. Design principles of I4.0.

Design Principle	Description
Interoperability (DP_1)	This is aimed at ensuring effective and systematic communication, information flow, and data sharing between all levels and entities in a system (i.e., devices, equipment, people, departments, and products) [31]. Cybersecurity, communication, and networking technologies such as IoT/IIoT, Internet of People (IoP), and Internet of Everything (IoE) are enablers for this principle [18–20,32].
Virtualization (DP_2)	This involves the ability of a system to represent, in real time, data from the physical world as virtual-world data. This can improve the decision maker's performance by enabling the simulation of "what-if" scenarios to identify problems and to test solutions [18,20,32–34]. While sensors, scanners, AV/R, and simulation platforms are recommended technologies [19,35], virtualization strongly depends on the company size and industry field [36].
Decentralization (DP_3)	This is the ability of a system to perform actions and take decisions autonomously. This would lead to more agile and flexible systems that can react and adapt faster to changes in the market in terms of their production processes. Examples of technologies that support decentralization are CPSs, embedded systems, communication and networking, AI, IoT, smart actuators, and sensors [18–20,36,37].
Real-time capability (DP_4)	This is the ability to track and analyze all data within a system in real time. This is aimed at improving the decision-making process by speeding up the response to failure, identifying anomalies in demand patterns or operation performance in advance, and performing corrective actions. Within an integrated SC, this capability can facilitate just-in-time supply between manufacturers and retailers, or suppliers and manufacturers [38]. Among the technologies that can support this capability, the following can be mentioned: cloud computing, AI, data analytics, BD tools, IoT/IIoT, smart sensors, and radio frequency identification (RFID)/real-time locating system (RTLS) devices [18,20,39].
Service orientation (DP_5)	This is aimed at providing customer-centered services as a new business strategy to increase value creation and profitability [20,21]. This ensures customer inclusion as products and services are offered to users [21]. In this context, the Internet of Service (IoS) can enable connection between CPSs and customers, with smart tools to provide them with a new service that integrates all parties within the value chain with updated information [18,19,40].
Modularity (DP_6)	This is aimed at improving the adaptation of businesses to changing requirements in the environment (i.e., fluctuating market demand and new product features). The smart factory can achieve flexible adaptation by enabling the *plug and play* principle to add, connect, or separate configurable modules as needed [21,41]. This capability can be supported by industrial robotics, additive manufacturing, BD, IoP/IoS/IoT/IIoT, simulation tools, and A/VR [42,43].
Smart products (DP_7)	Under I4.0, a smart product is an embedded device that can collect, store, update, and transfer data between the end-user and the entities involved in its production [32]. This can reduce the boundaries between the physical and digital worlds [18,19,44] and support the transformation of the product for recycling purposes, favoring the achievement of ecological and sustainable development goals [45].
Corporate social responsibility (CSR) (DP_8)	This ensures that businesses activities follow the "3P" principle (People-Planet-Profit), which involves a responsible balance between economic, environmental, and social compromises. Thus, activities in all companies must be performed considering ethical values, sustainability, environmental and social care, safety, and wealth [18,19,32,46]. Hence, CSR enables the design and implementation of sustainability practices to reduce resource usage, improve energy-efficient use, and reduce emissions [47].

3. Sustainability Aspects of I4.0 for Textile SMEs

Figure 1 presents an overview of a standard textile/apparel/garment SC [48,49]. Note that material flow starts at the "Fiber Manufacturer" level, where the amount of waste varies depending on several factors, such as the type of fiber being produced, the raw material cleaning and formation processes, and the efficiency of waste management practices. In 2015 alone, the textile industry consumed 53 million tons of textile fibers, of which 73% was landfilled or incinerated, and less than 1% was recycled for new clothing [49]. Then, at the "Textile Manufacturer" level, waste consists of damaged or scrap yarn, unfinished cones, unfinished fabric, and rejected colored fabric. Finally, at the "Apparel Maker" and "Retailer" levels, waste consists of overstock of development samples and apparel. It is important to highlight that, within the production levels, wet processing is performed, which leads to a major water footprint [49].

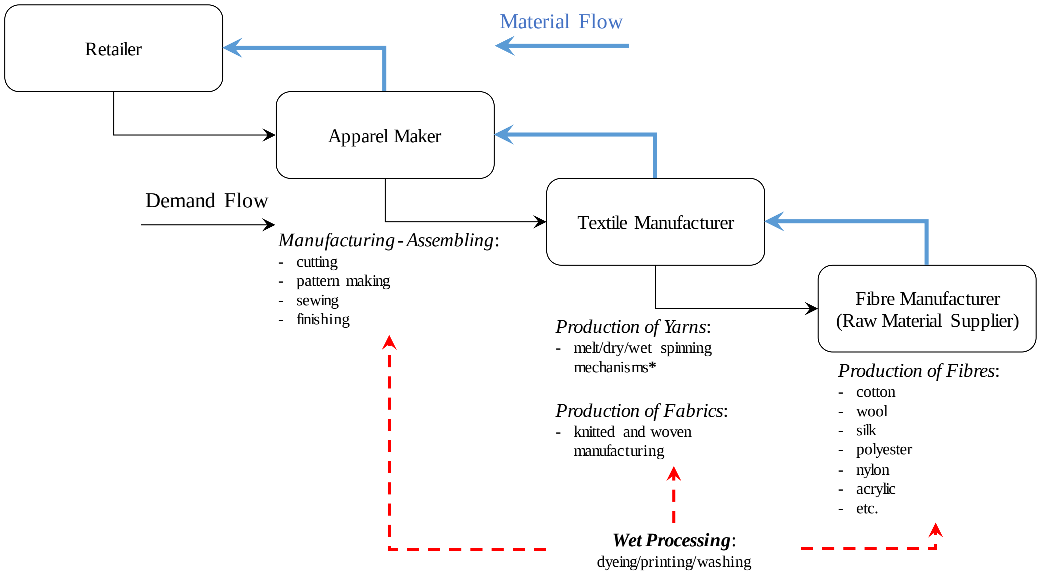

Figure 1. Processes within a textile SC (* note: some spinning mechanisms are not possible for certain types of fibres).

Given the role of the fashion industry in the generation of pollutants, sustainability must be considered within I4.0 implementation. Recently, the term circular economy (CE) has been coined to promote the responsible use of resources for sustainable, resilient, and innovative business models [50,51].

The main barrier that has been identified for implementing CE is the lack of proper information flow [52,53]. In this context, I4.0 technologies and digitalization can contribute to reducing this barrier and improving the economic, environmental, and social dimensions of sustainability in manufacturing processes [51]. The following were identified as environmentally friendly and socially responsible textile industry ventures under I4.0:

- Resource efficiency: Real-time monitoring systems, smart sensors, and data analytics can optimize the utilization of energy, water, and raw material resources throughout textile manufacturing processes [51,54–56].
- Predictive maintenance: IoT/IIoT and data analytics can support the identification and correction of operational problems before they lead to costly breakdowns. By proactively maintaining machinery, energy consumption can be optimized, reducing downtime and the need for emergency repairs.
- SC transparency and traceability: Through the use of blockchain, IoT/IIoT devices, and data analytics, stakeholders can track and verify the origin, production processes, and sustainability credentials of raw materials, ensuring ethical sourcing and responsible manufacturing practices [54,55,57–59].
- Waste reduction and recycling: By facilitating efficient data collection and advanced analysis, textile manufacturers can identify areas of waste generation and implement strategies to minimize it. Automation and robotics can reduce material waste by improving the precision of cutting, dyeing, and yarning operations. Also, the implementation of closed-loop systems enables the recycling and reuse (R&R) of textile waste [51,55–59].
- Reduction in the water footprint (WF): The WF is an indicator of the amount of fresh water utilized in the production or supply of the goods and services consumed by a particular person or group [60]. As presented in Figure 1, water is wasted throughout

most of the textile SC. Specifically, the following are I4.0 technologies and strategies that can be considered to reduce the textile WF:

- Real-time monitoring and analytics: the analysis of real-time water-usage data from sensors and waste-water discharge patterns can improve the accurate and prompt identification of water-usage inefficiencies, leaks, and excessive water consumption.
- Smart water management systems: Through IoT/IIoT, these systems can monitor water quality, temperature, turbidity, salinity, and flow rates to perform adjustments and control the water usage within the different stages of the production life cycle [61].
- Recycling and reuse: Waste-water treatment and purification systems equipped with advanced sensors and automation can recover and treat water from various stages of textile production. Treated water can then be reused for non-potable purposes such as cleaning, dyeing, or irrigation, reducing the need for fresh water intake.
- Simulation and digital twins: The simulation of diverse scenarios and parameters can be used to reduce water consumption, optimize dyeing/yarning processes, and improve overall efficiency. Digital twin technology enables real-time monitoring and optimization to perform adjustments in the manufacturing processes and minimize water usage while maintaining product quality [28].
- Precision dyeing and chemical management: Automation, robotics, and smart systems can optimize the control of the chemical parameters of the dyeing process (i.e., temperature, time, and chemical dosage) to minimize waste water associated with excessive rinsing and repeated dyeing cycles [56,62].
- SC collaboration: By engaging suppliers, manufacturers, and other stakeholders in water stewardship initiatives, water-efficient practices can be promoted throughout the SC. Sharing best practices, implementing water-saving technologies, and collectively addressing water-related challenges can support the reduction in the overall WF.

- Product customization and personalization: On-demand production and products tailored to individual customer preferences can be achieved with minimum overproduction and waste generation. This can reduce the environmental impact associated with unsold goods.
- Sustainable product development: Data analytics and simulation tools can optimize the design and development of sustainable textile products. Virtual prototyping and digital simulations enable textile manufacturers to test various materials and manufacturing processes, reducing the need for physical samples and iterations.
- Worker safety and well-being: The automation of hazardous tasks, such as repetitive and strenuous activities, can reduce the risk of work-related injuries. Furthermore, real-time monitoring systems can help identify potential health and safety risks, enabling prompt intervention and preventive measures.
- Circular economy (CE) initiatives: Through digital platforms and networks, textile manufacturers can collaborate with other stakeholders to enable product take-back programs, recycling initiatives, and the sharing of resources, promoting a more sustainable and circular textile ecosystem [51,55,57,58].Textiles are some of the least recycled products, and the CE concept has the potential to create significant value for textile companies, consumers, and the environment. Many companies are integrating reverse logistics within textile SCs to enable recycling, repairing, and remanufacturing processes [59].

4. Defining an Implementation Plan

I4.0 ventures must be driven by the market, customer, product, and/or enterprise innovation needs. If they are fully justified, then an implementation plan can be envisioned.

Figure 2 presents an integrative overview of three models that have been proposed for innovation-driven I4.0 implementations [63]:

- Linear Technology Push (LTP): This model consists of the sequential execution of several steps, where the innovation is driven by the creation of disruptive technologies and/or products that are expected to fulfill a market demand. Note that the development of disruptive technologies and/or products is supported by fundamental or basic research, and marketing is crucial to support the introduction of these into the market and create (or increase) its demand.
- Linear Model of Market Pull (LMP): Although this model is very similar to LTP regarding the main steps, the innovation is driven by actual (not expected) market needs. Hence, innovations are mainly reactive to the market needs and supported by applied research.
- Mixed Model of Rothwell and Zegveld (MR&Z): this model enables non-sequential steps and continuous feedback between all implementation stages and SC entities. Note that the MR&Z is more flexible as it is supported by basic and applied research, and considers expected and actual market needs.

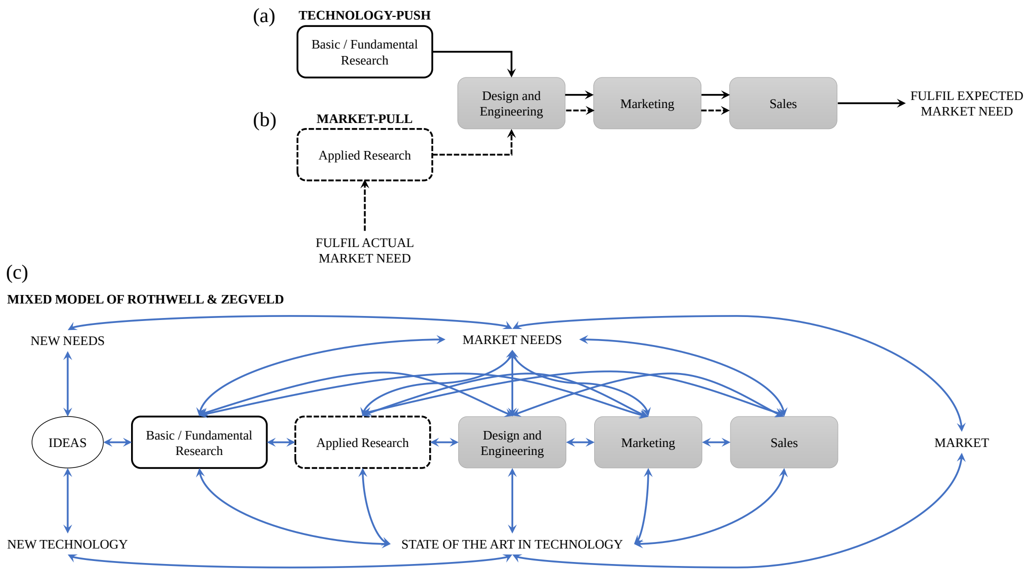

Figure 2. Innovation-driven models for I4.0 ventures: (**a**) Technology Push, (**b**) Market Pull, and (**c**) Rothwell and Zegveld.

Note that the first step of the innovation process consists in performing research to understand the current state of the market and technological needs. Although not explicitly explained, this research must consider the current enterprise's resources and vision regarding innovation. Hence, more detailed guidelines or implementation models are required for I4.0 ventures in SMEs.

In this work, the guideline model was structured as an integration of the MR&Z innovation model within the Six-Sigma continuous improvement model. Within the context of manufacturing systems, the DMAIC (define, measure, analyze, improve, and control) methodology was used as reference for Six-Sigma projects [64–66]. Figure 3 presents an overview of the implementation steps according to the DMAIC methodology. The following sections describe the integrated DMAIC steps with the MR&Z innovation model.

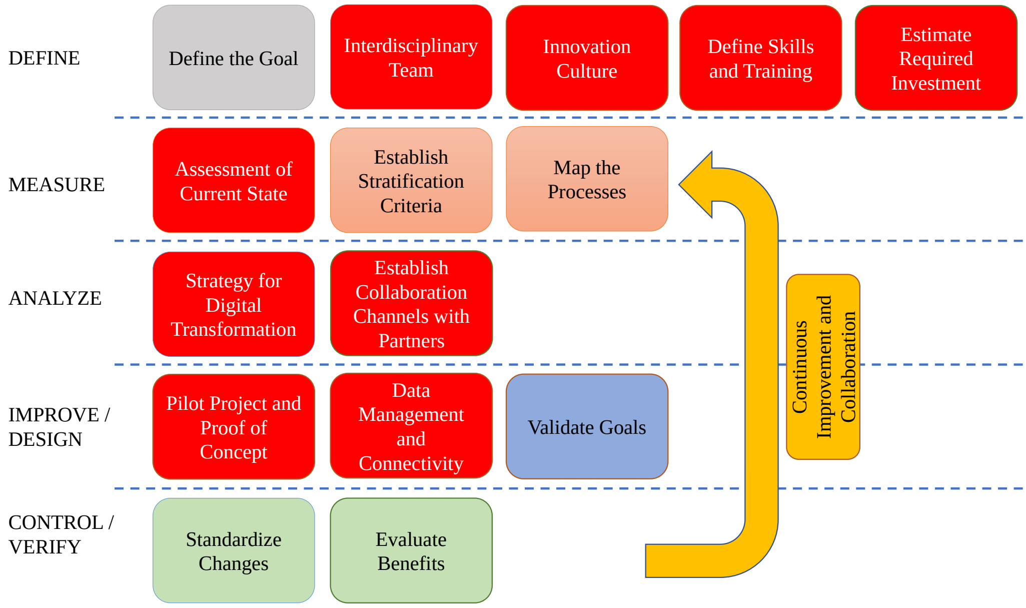

Figure 3. Work plan for a I4.0 Six-Sigma project.

4.1. Define

In this step, the project's scope is clarified, the problem is identified, and the targets to be achieved are defined [65]. As presented in Figure 4, basic and applied research is performed by the skilled team. This must be driven by the market and technology trends, and frequent feedback must be performed with production, marketing, and sales. Also, as reviewed in Section 3, sustainability principles and technologies have to be considered while performing basic and applied research. Hence, an interdisciplinary team must be gathered to perform this step.

Because SMEs are characterized by limited resources, it is recommended to focus on the "Market Pull" to reduce the uncertainty in the outcomes of the I4.0 implementation. Note that collaboration with production, marketing, and sales improves the *design thinking* process [67]. Although at this step this collaboration does not involve the "actual production" of the innovation, it contributes with its *a priori* assessment.

The proposed sets of elements for the "Define" step are presented in Figure 4. Note that additional strategic tools such as SCRAMPER and SWOT can be used to support the following key aspects:

- Interdisciplinary team: A cross-functional team should be established comprising members from different departments, including operations, IT, engineering, human resources, and management. This team will be responsible for overseeing the implementation process, coordinating efforts, and ensuring collaboration across the organization. Note that this team must be fully dedicated to the project, with the freedom to think outside existing company boundaries and guide the project to enable the company to understand the new strategic directions regarding technology, ways of working, and ecosystems [30]. It is recommended to study complementary concepts such as *design thinking* [67] and *open innovation* [68] for the execution of the team's tasks and look for support with universities working in I4.0 projects.
- Innovation culture: A culture of innovation and digital transformation should be fostered throughout the organization. Employees should be encouraged to contribute ideas, experiment with new technologies, and embrace change. The benefits of I4.0, such as improved efficiency, productivity, sustainability, and customer satisfaction, should be emphasized.
- I4.0 Skills and training: A set of skills and training is defined for the implementation team. This involves training in data analytics, IoT/IIoT, automation, programming,

and digital systems. Currently, universities working in I4.0 strategies can support this set of skills [69,70].

- Required investment: The economic feasibility of the project must be studied, considering its competitive and financial outcomes. The return on investment (ROI) can be calculated for this case, considering the costs associated with training; hardware (sensors, connectivity devices, data storage); software; and processing times for the required tasks.

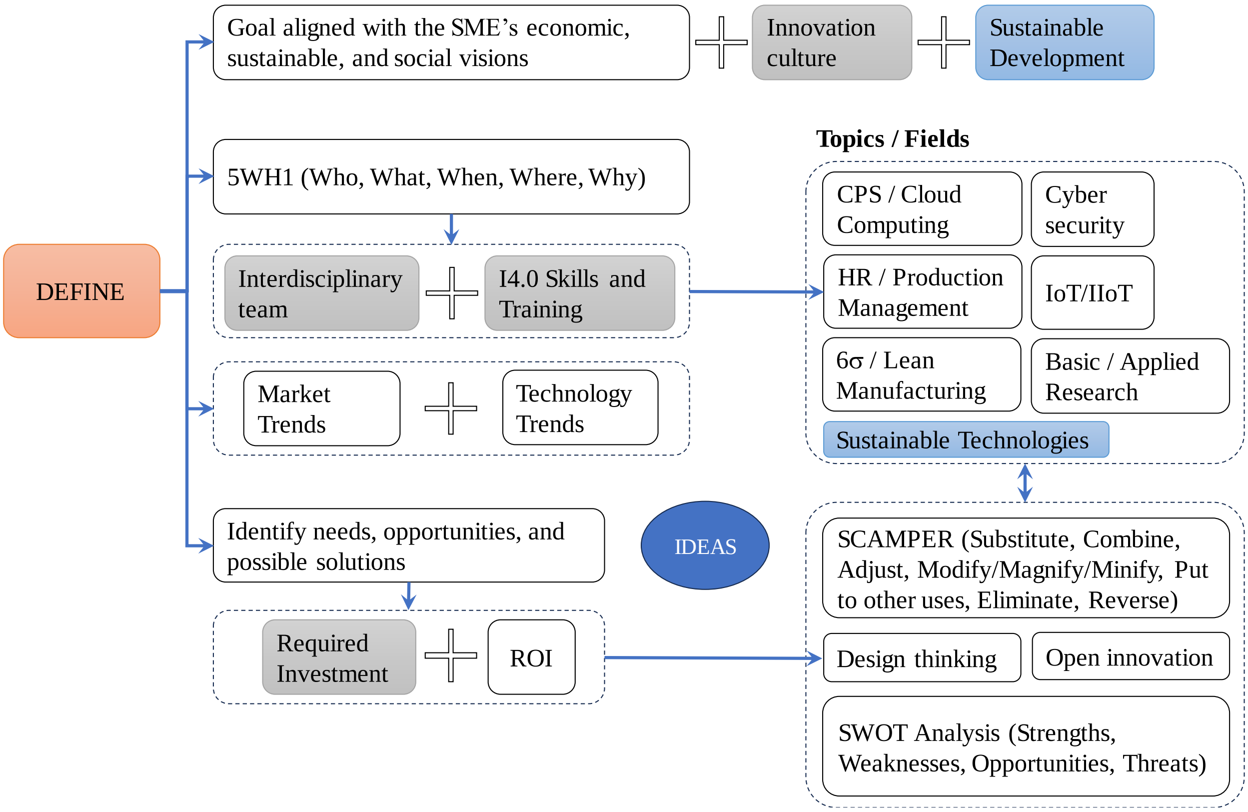

Figure 4. Proposed elements for the I4.0 Define step.

4.2. Measure

This step consists in establishing reliable/applicable metrics to monitor key processes' performance and understand their progress towards the objectives established in the "Define" step [66]. The current state of the textile manufacturing operations, including infrastructure, processes, and workforce capabilities, can be evaluated through a specific I4.0 test known as the "readiness assessment". As presented in Figure 5, this can provide important feedback for the "identify needs, opportunities, and possible solutions" tasks within the previous "Define" step and provide insight to identify associated metrics.

In practice, readiness assessment is performed through the evaluation of maturity models (MMs), which consider the I4.0 design principles (DPs) [19]. MMs are commonly presented in the form of surveys that assess the company from several perspectives, resulting in suitability scores that help companies to understand their position in regard to I4.0, revealing their weak and strong sides, and set future targets and strategies [19]. Figure 5 presents an overview of selected MMs that have been reported in the I4.0 literature and how these provide feedback for activities in the "Define" step. Then, Figure 6 presents an overview of these MMs' features and maturity levels.

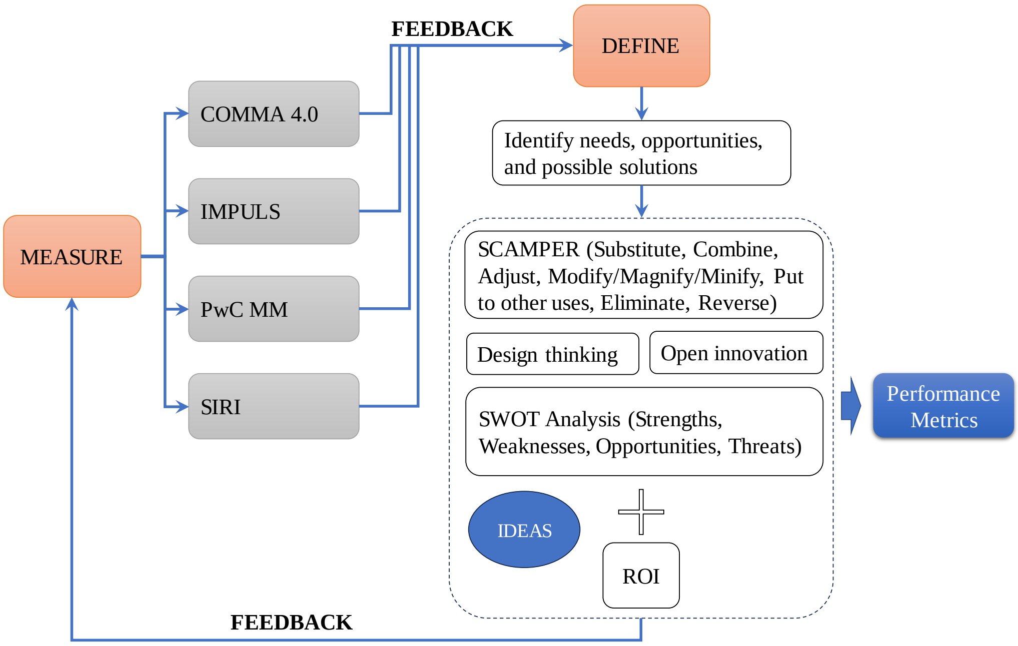

Figure 5. Proposed elements for the I4.0 Measure step.

4.3. Analyze

In this step, different ways to reduce the gap between the current and desired performance are identified based on the previous "Define" and "Measure" steps [66]. Thus, this step is focused on the analysis, interpretation, and proposal of strategies for the elimination/minimization of the identified problems or execution plans for the identified opportunities. Note that the actual execution of the innovation is to be started in this step. Figure 7 presents an overview of the main tasks to be performed:

- Development of a digital transformation strategy: The identification of the specific technologies and solutions that align with the business needs.Factors such as automation, data analytics, IoT/IIoT, AI, and cloud computing are considered. Figure 7 lists some examples of software platforms that enable the simulation of IIoT devices and protocols, 3D printing, and cybersecurity assessment.
- Collaboration with partners: This involves engagement with technology providers, consultants, research institutions, and industry peers to gain insights, share best practices, and collaborate on I4.0 initiatives. External expertise and partnerships are leveraged to accelerate the digital transformation journey. Here, HI is very important for collaborating with external organizations and working with R&D institutes such as universities or industry organizations to speed up the "open" digital innovation [17].

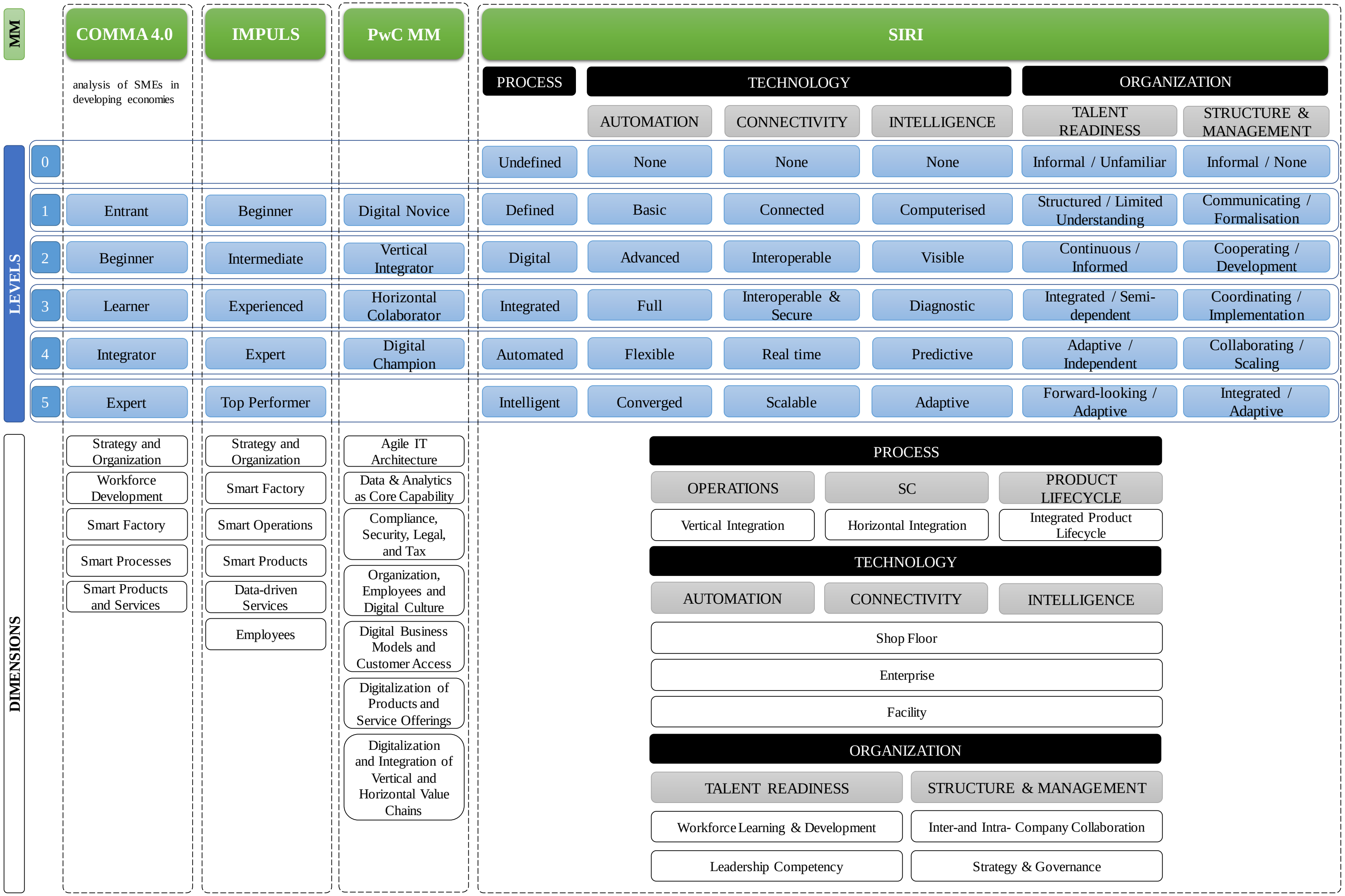

Figure 6. Overview of Selected MMs for I4.0 Measure step: COMMA 4.0 [71], IMPULS [72], PwC Maturity Model [30], and Singapore Smart Industry Readiness Index (SIRI) [73].

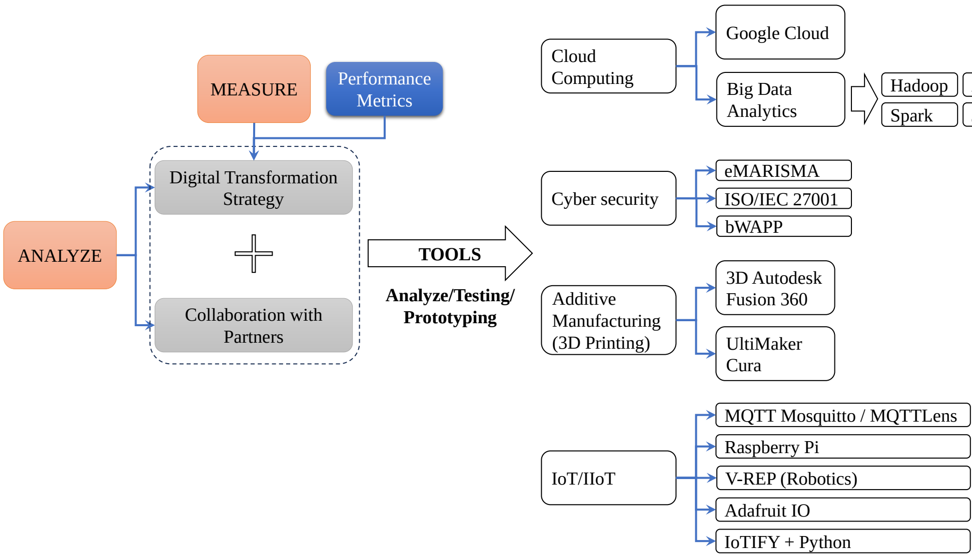

Figure 7. Proposed Elements for the I4.0 Analyze step.

4.4. Improve/Design

In this stage, the actual innovation is developed to achieve the desired performance (the "as-it-should-be" state), as established in the "Define", "Measure", and "Analyze" steps [66,74]. Figure 8 presents an overview of the main tasks to be performed in this step.

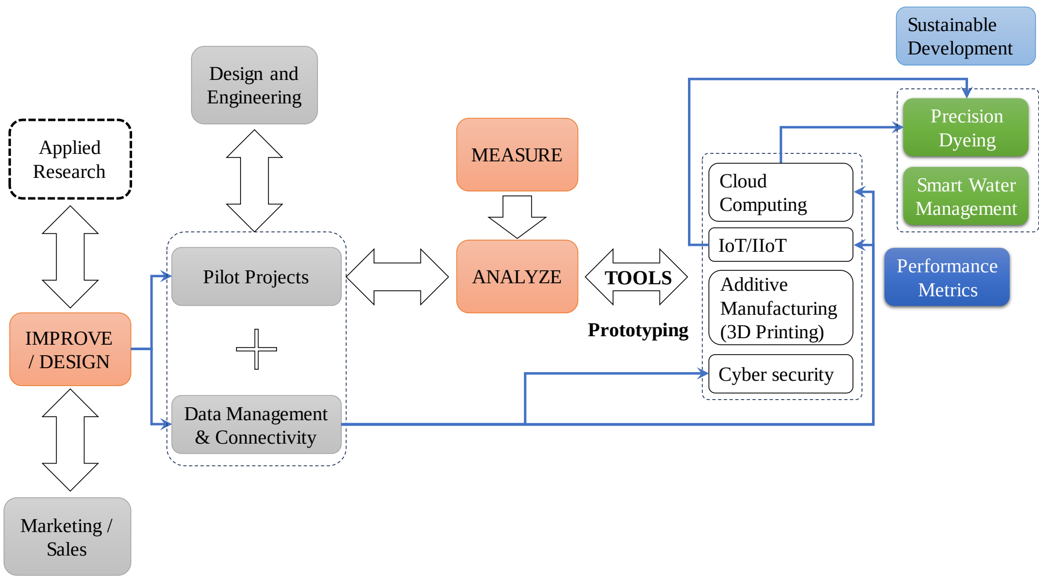

Figure 8. Proposed elements for the I4.0 Improve/Design step.

- Pilot projects and proof of concepts: The implementation of small pilot projects is recommended to test and validate the effectiveness of selected I4.0 technologies. These projects can serve as proof of concepts and allow for fine-tuning before scaling up to larger implementations. The continuous monitoring and evaluation of performance metrics (see the "Measure" and "Analyze" steps) are important to evaluate the results' impact and benefits [30].

Although it is important to mention that the economic benefits of the innovation are not always easy to calculate during the initial tests, and not every project will succeed in the first attempt, the learning outcome can provide valuable data and experience to reduce failure risk in the following iteration of the DMAIC process. In contrast, evidence from early successes can gain buy-in from the organization and secure funding for a larger project.

Hence, a crucial step in the pilot project development is to pick the right project. Figure 9 presents the I4.0 pilot project opportunities identified by PricewaterhouseCoopers (PwC) [30]. For the purposes of the present work, those more suitable within textile SMEs were marked.

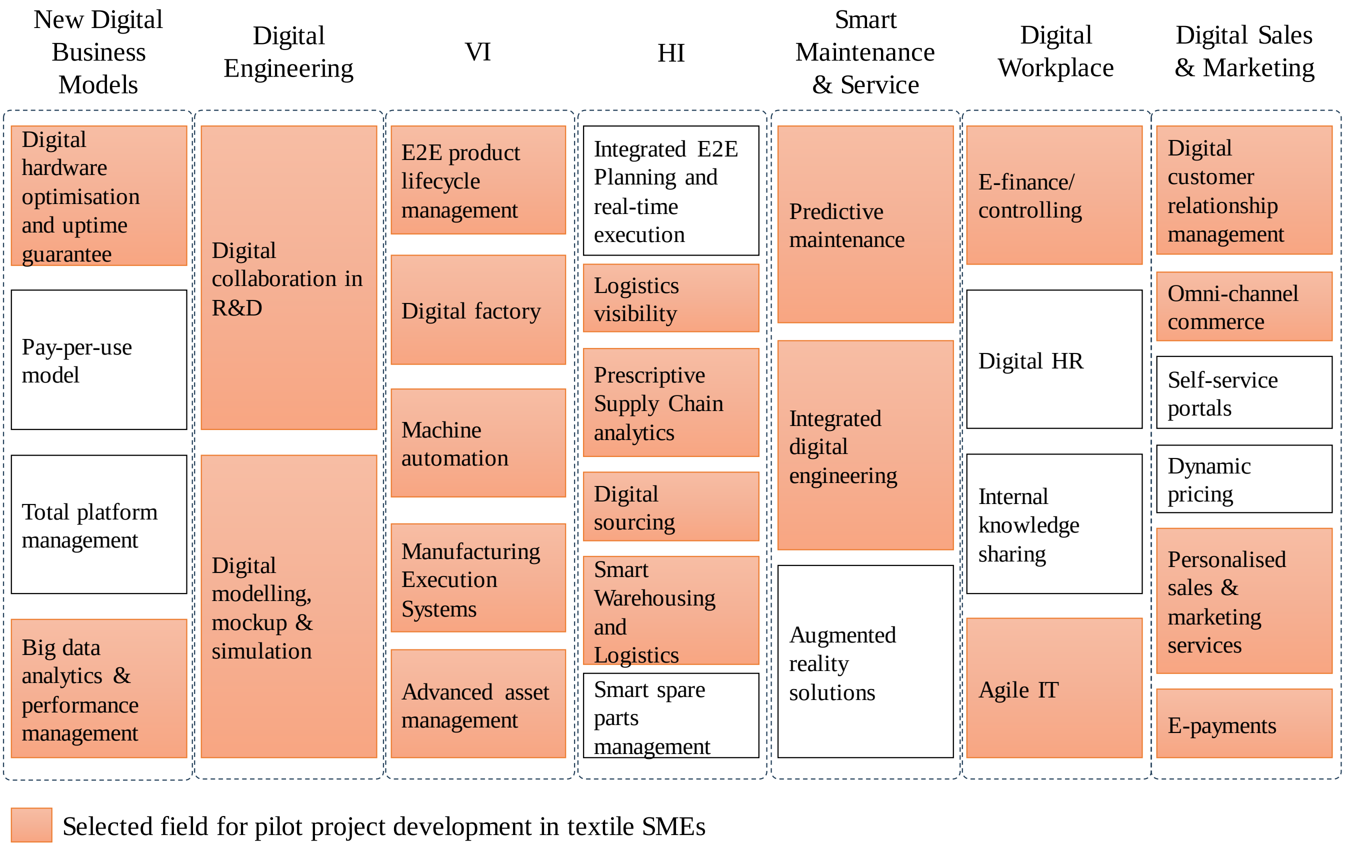

Figure 9. Selected 4.0 pilot opportunities along the full vertical and horizontal operational value chains in textile SMEs (edited from [30]).

Entities that can contribute to HI and *open innovation* are laboratories and universities [69,70]. As an example of a pilot project that has been supported by universities, the Textile Learning Factory 4.0 at the Institut für Textiltechnik der RWTH Aachen University in Aachen, Germany, proposed a framework to differentiate current factory environments and explain the migration process to a future I4.0 environment [69]. Two levels were defined, with some recommendations regarding the technologies to apply for a migration plan:

- Level 1—Current-state operation (lean): This serves as a realistic, good-practice industry environment in which the main lean tools and methods such as SMED, value stream mapping, Five-S, Kanban (pull systems), and *poka-yoke* (error-proofing) have been implemented. This level is used to train and teach participants the required methods and tools to conduct a digital transformation in a realistic factory environment.
- Level 2—Future-state operation (I4.0): This is used to showcase the potential of state-of-the-art I4.0 applications directly after the hands-on training in Level 1. The following I4.0 applications are considered: condition monitoring, digital assistant systems, and digital performance management for the first implementation; then, automated material supply, advanced analytics for yield, energy and throughput, real-time line balancing, advanced analytics for breakdown prevention, self-adjusting workstations, in-line quality control with machine feedback, human–robot collaboration, and tailored production components (3D printing) are addressed.

The development of I4.0 toolboxes and smart manufacturing toolkits has been proposed to inform and guide SMEs within their digitalization processes [75]. Toolkits have been developed for fabrication/manufacturing, maturity levels, design and simulation, robotics and automation, sensors and connectivity, cloud/storage, data analytics, and business management. The technically oriented toolboxes have been complemented by selected business management tools. The reason for this last toolbox is to successfully deploy the SM toolkit and change the SMEs' mindset to improve the organizational culture and other management aspects [75].

- Data management and connectivity: A robust data management system is established to collect, analyze, and interpret data from various sources within the manufacturing processes. Secure connectivity between devices, machines, and systems is ensured to enable real-time data exchange and communication (IoT/IIoT).

Note that, in contrast to the "Analyze" step, the recommended tools are to be used mainly for prototyping, as proof of concepts and pilot projects are needed. Also, as the "Market Pull" focus is suggested to reduce the uncertainty regarding the impact of the innovation, applied research based on sustainability principles and technologies and marketing/sales feedback are encouraged (as established by the MR&Z model). Finally, IoT/IIoT and cloud computing can be focused on enabling precision dyeing and smart water management to reduce the environmental impact of the textile industry.

4.5. Control/Verify

This step is focused on (a) setting the mechanisms for ongoing monitoring and institutionalizing the achieved innovation, and (b) ensuring that all employees perform the improved processes in a uniform manner [66]. Hence, a continuous improvement and adaptation program (CI&AP) must be established to continuously monitor, analyze, improve, and protect the implemented innovation and verify its compliance with the evolving technologies and market dynamics. Finally, as presented in Figure 10, once the technological aspects of the established innovation are verified, the CI&AP must be matched with the SME's economic, sustainable, and social visions to support the innovation culture for I4.0.

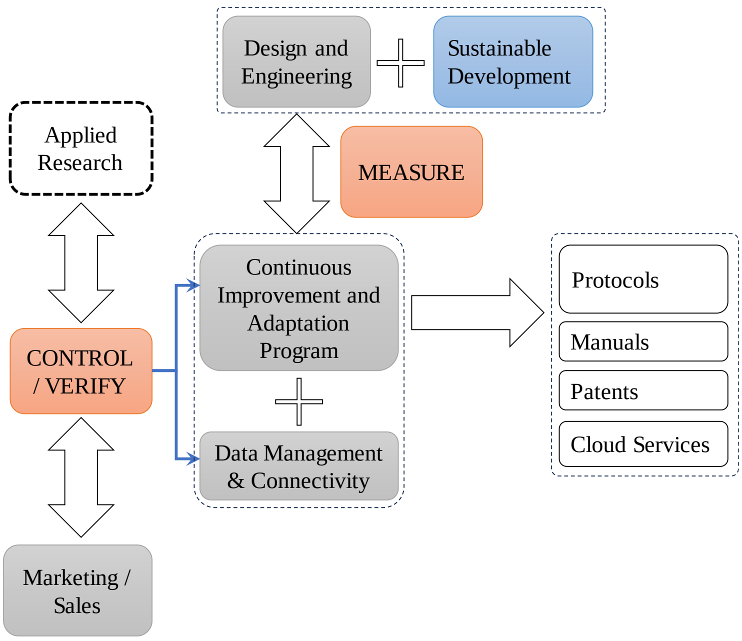

Figure 10. Proposed elements for the I4.0 Control/Verify step.

5. Discussion on the Applicability of the Model

As the present work is focused on supporting SMEs for I4.0 ventures, the Six-Sigma DMAIC methodology was considered. This is because Six Sigma is well-established in SME lean manufacturing projects for continuous improvement. This also enables the application of the methodology for other SMEs. Then, by integrating the MR&Z model, the appropriate relationships between the SME departments and activities are identified to encourage and support innovation, which is a key feature of I4.0 ventures.

Figures 3–10 present the steps of the adapted DMAIC model, highlighting key aspects such as: the specific skills of the interdisciplinary team; assessment tools (ROI, SCAMPER, SWOT, COMMA 4.0, IMPULS, eMARISMA, etc.); and implementation/prototyping tools (Hadoop, Spark, eMARISMA, UltiMaker, MQTT, IoTIFY, etc.). These are provided in accordance with the objectives of the DPs, which consist of reducing the knowledge gap regarding I4.0 concepts, benefits, and implementation steps [18,19].

As a brief example following the proposed method, Figure 11 presents an overview of the implementation steps for a sock manufacturing SME:

- Define: The family SME is aimed at providing the best-quality socks within the local market; however, the current manufacturing technology is outdated, and production is limited to 50 product units per day. Also, because there are many competitors in the market, demand for the main product has been decreasing in the last few years. Thus, the SME wants to improve its product or create a new product with higher market demand.

As shown in Figure 11a, the manufacturing process (excluding raw material production) sequentially consists of knitting, sewing, dyeing (optional), ironing, packaging, and shipping. Specifically, the first three processes are performed by human-assisted machines, which are not scalable for automation or IoT technologies (null flexibility). This is further supported by a SWOT analysis.

Based on Figure 9, and considering the current infrastructure and SME resources, it is determined that there are I4.0 pilot project opportunities in "machine automation" and "manufacturing execution systems" (VI), as well as "integrated digital engineering" (smart maintenance and services). Note that these opportunities are associated with product development; hence, they are directly related to the SME's objective of improving or creating a product with a higher market demand.

A market trend analysis is performed to determine that socks for people with diabetes is an emerging local market, specially with esthetic and colorful designs. Basic research is performed to determine the specific knitting and raw material requirements, lending support to the non-viability of the current knitting machines. Then, applied research is performed to identify more recent machines and how these can be adapted to manufacture the new product. Note that these research activities are performed with sustainable development principles to consider reduction in product waste, the low consumption of oils/energy, and minimum cleaning requirements. The same SWOT analysis supports the strengths and opportunities of the SME, which comprises few decision levels to execute the I4.0 venture.

- Measure: A more comprehensive overview of the current capability of the SME for I4.0 (maturity level) is provided by the IMPULS test, indicating Level 0 "outsider" (see Figure 11b). This is a lower level than "beginner", which is the first significant level listed in Figure 6. These results are consistent with the current absence of automation, interconnectivity, and IoT technologies in the manufacturing SME.

Feedback is provided with the results obtained in the "Define" step to refine the applied research regarding the new equipment (knitting, sewing, and dyeing machines). Also, the connectivity protocols and additional devices (such as sensors) to enable their on-line tracking and monitoring are studied. A first ROI estimate is calculated to evaluate the economic viability of the I4.0 technology implemented in any of the main manufacturing processes (see Figure 11a). Note that at this point an estimate of the amount of the manufactured product and waste generated in these processes should be performed for the future assessment of the improvement.

- Analyze: Here, it is determined that knitting is the critical process to be improved. Also, as it is the initial process, it is the ideal starting point for the consistent digitalization of the entire manufacturing system in the future. Automated machines that can produce different knitting patterns (such as those needed for the intended new product) with sewing are identified on the market with IIoT capabilities. Due to the improved production rates, a single machine of this type can replace the current SME's fleet of four machines.
- Improve: HI is crucial for this step, as investment without testing the new technology can compromise the SME's resources and stability. Contact with manufacturers and suppliers facilitates demonstrations, customization, and complementary connectivity systems for the SME before the acquisition of the technology.

After these tests, feedback and acquisition are performed, and the SME should implement sensors for the remote monitoring of failures and the amount of manufactured products per type. As knitting is the first production process, it can be linked with an updated order receiving system.

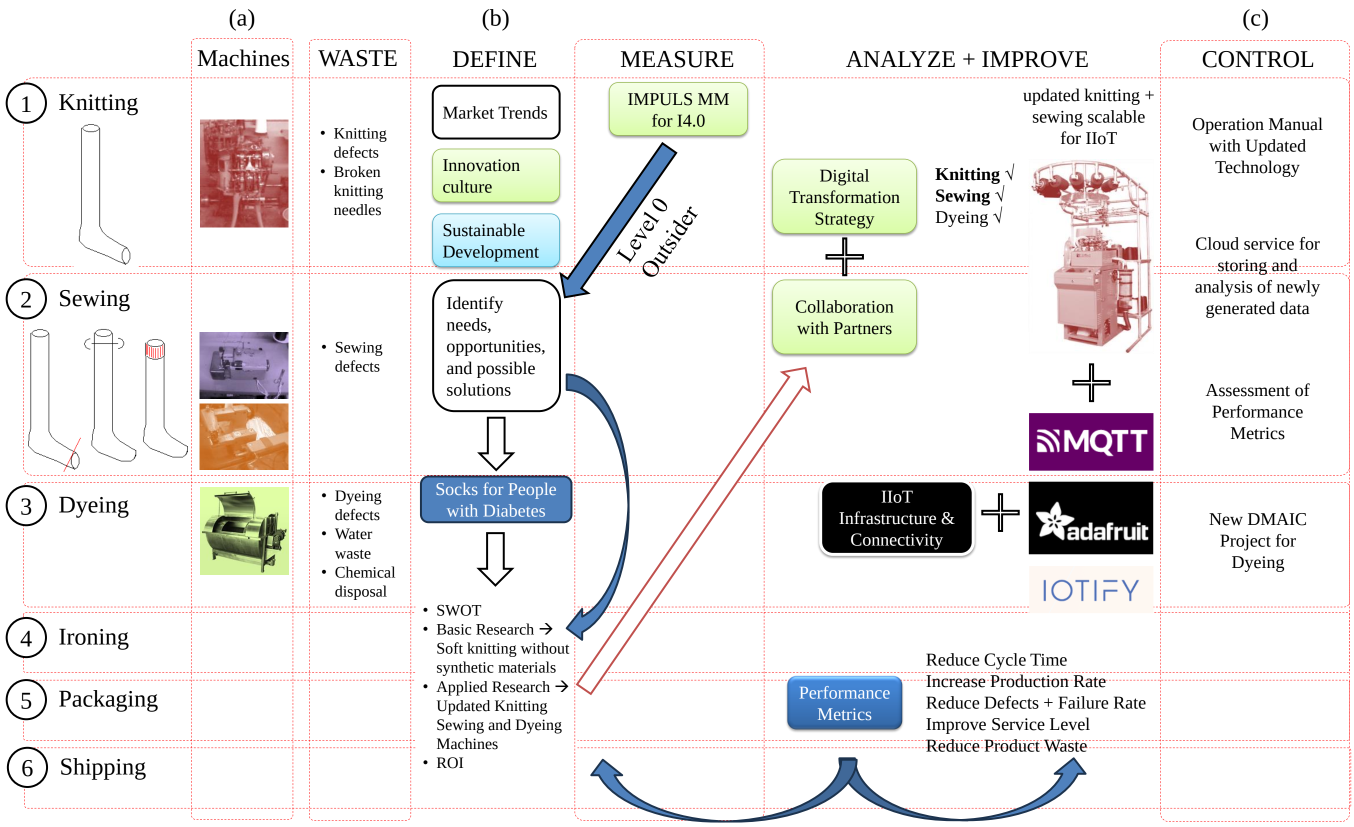

Figure 11. Discussed I4.0 pilot project for a sock manufacturing SME: (**a**) defining the main manufacturing processes and current technology (machines), (**b**) activities associated with the initial "Define" and "Measure" steps, (**c**) activities associated with the final "Control" step.

The linked order–knitting system can provide data for product forecasting, which can improve the raw material supply (optimal lot size), failure rate, and consumer behavior. Cloud computing services, such as Adafruit IO, IoTIFY, and MQTT, can be used to store and track variables associated with these data.

- Control: By establishing and tracking the performance metrics defined in the previous steps, the benefits of the implementation system can be measured. The refinement of the steps followed to operate the new system for each product is performed to create a set of standard steps documented in an operation manual. As presented in Figure 11c, once this process is improved, the other processes in the SME's SC can follow:
  - RFID/QR devices/codes/sensors can be set at the packaging station to record the status of the final products and enable tracking for shipping;
  - This feedback can enhance the measurement of variables such as cycle time, number of failures, and service level for customer behavior analytics and demand forecasting for smarter raw material procurement;
  - By upgrading the dyeing machine, precision dyeing can reduce the waste generated by damaged products and waste water due to excessive chemical release. The cloud computing services Adafruit IO, IoTIFY, MQTT, etc., can be used to store and track variables associated with these data and enable a more extensive automated analysis for the improvement of the whole SC.

It is important to mention that I4.0 is not limited to the discussed case study. For example, in [76], the design of smart socks for IoT analysis was presented. While some IoT and data tools are proposed in the present work, there are many other technologies. Recent extensive reviews regarding IoT and data tools within the context of I4.0 can be found in [77,78].

6. Conclusions

I4.0 technologies offer benefits to companies in the field of manufacturing. In particular, for textile companies, they can have economic but also social and environmental benefits. Aspects such as water pollution and the water footprint can be reduced with the digitization of the textile SC. However, an implementation or migration process to an I4.0 system is a difficult challenge, because there are various aspects to consider; therefore, there is no comprehensive guide for these processes.

This work was initially focused on reviewing and clarifying terms and concepts in order to understand what I4.0 is, as well as to understand the information presented in the specialized literature and identify when a project is focused on a CPS or on a smart factory. Then, an analysis was conducted on how I4.0 can contribute to improving textile SMEs, specifically, to reduce their impact on the environment.

With this review and analysis, the work focused on defining a guide for the development of an I4.0 project. To facilitate understanding, this was established as a Six-Sigma project, and the application of maturity models (MMs) and design principles (DPs) was a fundamental part of its planning. The skills required by the interdisciplinary team are identified, and the economic requirements for the project are also identified at this stage.

The implementation of the proposed Six-Sigma project, through the DMAIC methodology, was reinforced with the introduction of the MR&Z model to encourage innovation, which is a key feature of I4.0 ventures. While this work focused on textile SMEs, the methodology can be adapted to other SMEs, as it was based on DMAIC, which is an established methodology for continuous improvement projects. In each step, key recommendations and tools were highlighted for analysis and prototyping. Finally, a discussion regarding the applicability of the model was performed with a case study.

Note that HI is important for the development of any pilot project, as consultancy and research institutes such as universities can provide valuable feedback for appropriate implementation with more accessible funding alternatives. As a consequence, failure risk can be reduced, which also improves the practical learning outcomes.

A limitation of the present work was the absence of a portfolio of detailed implementation case studies in SMEs in Mexico. While this was associated with the restrictions described in Section 1, we acknowledged the need for this resource. Nevertheless, it is expected that the present work can provide reference guidelines for the development and future generation of such case studies.

Another limitation, due to the vast range of implementation opportunities in SMEs, was that detailed guidelines for the specific use of some tools, such as MQTT for textile IoT, were not provided. Hence, a future work focused on providing such tutorial material is recommended.

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References

1. Tjahjono, B.; Esplugues, C.; Ares, E.; Pelaez, G. What does Industry 4.0 mean to Supply Chain? *Procedia Manuf.* **2017**, *13*, 1175–1182. [CrossRef]
2. Pereira-Carvalho, N.G.; Cazarini, E. Industry 4.0—What Is It? In *Industry 4.0: Current Status and Future Trends*; Hamilton-Ortiz, J., Ed.; Intech: London, UK, 2020; pp. 3–11.
3. Pereira-Carvalho, A.C.; Pereira-Carvalho, A.P.; Pereira-Carvalho, N.G. Industry 4.0 Technologies: What Is Your Potential for Environmental Management? In *Industry 4.0: Current Status and Future Trends*; Hamilton-Ortiz, J., Ed.; Intech: London, UK, 2020; pp. 29–44.
4. Raina, A.; Gries, T. Industry 4.0: Understanding Needs and Challenges of Technical Textiles Industry. *Int. J. Text. Sci. Eng.* **2017**, *2017*, 1–15.
5. Dalenogare, L.S.; Benitez, G.B.; Ayala, N.F.; Frank, A.G. The expected contribution of Industry 4.0 technologies for industrial performance. *Int. J. Prod. Econ.* **2018**, *204*, 383–394. [CrossRef]
6. Frank, A.G.; Dalenogare, L.S.; Ayala, N.F. Industry 4.0 technologies: Implementation patterns in manufacturing companies. *Int. J. Prod. Econ.* **2019**, *210*, 15–26. [CrossRef]
7. Shishoo, R. The importance of innovation-driven textile research and development in the textile industry. In *Global Textile and Clothing Industry*; Shishoo, R., Ed.; Woodhead Publishing Limited: Sawston, UK, 2012; pp. 55–76.
8. Ghoreishi, M.; Happonen, A. The Case of Fabric and Textile Industry: The Emerging Role of Digitalization, Internet-of-Things and Industry 4.0 for Circularity. In Proceedings of the 6th International Congress on Information and Communication Technology (ICICT 2021), London, UK, 25–26 February 2021; Springer: Berlin/Heidelberg, Germany, 2022; pp. 189–200.
9. Chen, C.L. Value Creation by SMEs Participating in Global Value Chains under Industry 4.0 Trend: Case Study of Textile Industry in Taiwan. *J. Glob. Inf. Technol. Manag.* **2019**, *22*, 120–145. [CrossRef]
10. Bai, C.; Dallasega, P.; Orzes, G.; Sarkis, J. Industry 4.0 technologies assessment: A sustainability perspective. *Int. J. Prod. Econ.* **2020**, *229*, 107776. [CrossRef]
11. Behr, O. Fashion 4.0—Digital innovation in the fashion industry. *J. Technol. Innov. Manag.* **2018**, *2*, 1–9.
12. Dikhanbayeva, D.; Aitzhanova, M.; Shehab, E.; Turkyilmaz, A. Analysis of Textile Manufacturing SMEs in Kazakhstan for Industry 4.0. *Procedia CIRP* **2022**, *107*, 888–893. [CrossRef]
13. Majumdar, A.; Garg, H.; Jain, R. Managing the barriers of Industry 4.0 adoption and implementation in textile and clothing industry: Interpretive structural model and triple helix framework. *Comput. Ind.* **2021**, *125*, 103372. [CrossRef]
14. Masood, T.; Sonntag, P. Industry 4.0: Adoption challenges and benefits for SMEs. *Comput. Ind.* **2020**, *121*, 103261. [CrossRef]
15. Najera-Ochoa, J. Model of Competitiveness for the Textile and Clothing Industry in Mexico. *Univ. Empresa* **2015**, *17*, 37–68.
16. Xu, M.; David, J.M.; Kim, S.H. The Fourth Industrial Revolution: Opportunities and Challenges. *Int. J. Financ. Res.* **2018**, *9*, 90–95. [CrossRef]
17. Zhou, K.; Liu, T.; Zhou, L. Industry 4.0: Towards future industrial opportunities and challenges. In Proceedings of the 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD 2015), Zhangjiajie, China, 15–17 August 2015; IEEE: Piscataway, NJ, USA, 2015; pp. 2147–2152.
18. Hermann, M.; Pentek, T.; Otto, B. Design Principles for Industrie 4.0 Scenarios. In Proceedings of the 49th Hawaii International Conference on System Sciences (HICSS 2016), Koloa, HI, USA, 5–8 January 2016; IEEE: Piscataway, NJ, USA, 2016.

19. Dikhanbayeva, D.; Shaikholla, S.; Suleiman, Z.; Turkyilmaz, A. Assessment of Industry 4.0 Maturity Models by Design Principles. *Sustainability* **2020**, *12*, 9927. [CrossRef]
20. Sisodia, A.; Jindal, R. A meta-analysis of industry 4.0 design principles applied to the health sector. *Eng. Appl. Artif. Intell.* **2021**, *104*, 104377. [CrossRef]
21. Habib, M.K.; Chimson, I.C. Industry 4.0: Sustainability and Design Principles. In Proceedings of the 20th International Conference on Research and Education in Mechatronics (REM 2019), Wels, Austria, 23–24 May 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 1–8.
22. Hozdic, E. Smart Factory for Industry 4.0: A Review. *Int. J. Mod. Manuf. Technol.* **2015**, *7*, 28–35.
23. Chen, B.; Wan, J.; Shu, L.; Li, P.; Mukherjee, M.; Yin, B. Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges. *IEEE Access* **2018**, *6*, 6505–6519. [CrossRef]
24. Raff, S.; Wentzel, D.; Obwegeser, N. Smart Products: Conceptual Review, Synthesis, and Research Directions. *J. Prod. Innov. Manag.* **2020**, *37*, 379–404. [CrossRef]
25. Sengupta, J.; Ruj, S.; Bit, S.D. A Comprehensive Survey on Attacks, Security Issues and Blockchain Solutions for IoT and IIoT. *J. Netw. Comput. Appl.* **2020**, *149*, 102481. [CrossRef]
26. Jaidka, H.; Sharma, N.; Singh, R. Evolution of IoT to IIoT: Applications & Challenges. In Proceedings of the International Conference on Innovative Computing & Communications (ICICC 2020), Delhi, India, 21–23 February 2020; SSRN: Rochester, NY, USA, 2020; pp. 1–6.
27. Uhlmann, E.; Hohwieler, E.; Geisert, C. Intelligent Production Systems in the Era of INDUSTRIE 4.0—Changing Mindsets and Business Models. *J. Mach. Eng.* **2017**, *17*, 5–24.
28. VanDerHorn, E.; Mahadevan, S. Digital Twin: Generalization, characterization and implementation. *Decis. Support Syst.* **2021**, *145*, 113524. [CrossRef]
29. Costa, F.S.; Nassar, S.M.; Gusmeroli, S.; Schultz, R.; Conceicao, A.G.S.; Xavier, M.; Hessel, F.; Dantas, M.A.R. FASTEN IIoT: An Open Real-Time Platform for Vertical, Horizontal and End-To-End Integration. *Sensors* **2020**, *20*, 5499. [CrossRef]
30. Geissbauer, R.; Vedso, J.; Schrauf, S. *Industry 4.0: Building the Digital Enterprise*; PricewaterhouseCoopers, PwC: London, UK, 2016. Available online: https://www.pwc.com/gx/en/industries/industry-4-0.html (accessed on 10 May 2023).
31. Schuh, G.; Potente, T.; Hauptvogel, A. Sustainable increase of overhead productivity due to cyber-physical systems. In Proceedings of the 11th Global Conference on Sustainable Manufacturing, Berlin, Germany, 23–25 September 2013; GCSM: Leeds, UK, 2013; pp. 332–335.
32. Ghobakhloo, M. The future of manufacturing industry: A strategic roadmap toward Industry 4.0. *J. Manuf. Technol. Manag.* **2018**, *29*, 910–936. [CrossRef]
33. Syberfeldt, A.; Holm, M.; Danielsson, O.; Wang, L.; Brewster, R.L. Support Systems on the Industrial Shop-floors of the Future—Operators' Perspective on Augmented Reality. *Procedia CIRP* **2016**, *44*, 108–113. [CrossRef]
34. Liu, Q.; Zhang, H.; Leng, J.; Chen, X. Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system. *Int. J. Prod. Res.* **2019**, *57*, 3903–3919. [CrossRef]
35. Paelke, V. Augmented Reality in the Smart Factory: Supporting Workers in an Industry 4.0. Environment. In Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA), Barcelona, Spain, 16–19 September 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 1–4.
36. Brettel, M.; Friederichsen, N.; Keller, M.; Rosenberg, M. How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective. *Int. J. Mech. Aerosp. Ind. Mechatron. Manuf. Eng.* **2014**, *8*, 37–44.
37. Bartodziej, C.J. *The Concept Industry 4.0: An Empirical Analysis of Technologies and Applications in Production Logistics*; Springer: Wiesbaden, Germany, 2017.
38. Rosin, F.; Forget, P.; Lamouri, S.; Pellerin, R. Impacts of Industry 4.0 technologies on Lean principles. *Int. J. Prod. Res.* **2020**, *58*, 1644–1661. [CrossRef]
39. Chanchaichujit, J.; Tan, A.; Meng, F.; Eaimkhong, S. *Healthcare 4.0: Next Generation Processes with the Latest Technologies*; Palgrave Macmillan: Singapore, 2019.
40. Gebauer, H.; Edvardsson, B.; Bjurko, M. The impact of service orientation in corporate culture on business performance in manufacturing companies. *J. Serv. Manag.* **2010**, *21*, 237–259. [CrossRef]
41. Mittal, S.; Khan, M.A.; Romero, D.; Wuest, T. Smart manufacturing: Characteristics, technologies and enabling factors. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2019**, *233*, 1342–1361. [CrossRef]
42. Kumar, A. Methods and Materials for Smart Manufacturing: Additive Manufacturing, Internet of Things, Flexible Sensors and Soft Robotics. *Manuf. Lett.* **2018**, *15*, 122–125. [CrossRef]
43. Torn, I.A.R.; Vaneker, T.H.J. Mass personalization with industry 4.0 by SMEs: A concept for collaborative networks. *Procedia Manuf.* **2019**, *28*, 135–141. [CrossRef]
44. Nunes, M.L.; Pereira, A.C.; Alves, A.C. Smart products development approaches for Industry 4.0. *Procedia Manuf.* **2017**, *13*, 1215–1222. [CrossRef]
45. United Nations. *The Sustainable Development Goals Report 2016*; UN DESA: New York, NY, USA, 2016.
46. Adamik, A.; Nowicki, M. Pathologies and Paradoxes of Co-Creation: A Contribution to the Discussion about Corporate Social Responsibility in Building a Competitive Advantage in the Age of Industry 4.0. *Sustainability* **2019**, *11*, 4954. [CrossRef]
47. Whirlpool Corporation. *2017 Sustainability Report*; Whirlpool Corporation: Benton Harbor, MI, USA, 2017.

48. Damodaram, A.K.; Ravindranath, K. Cloud Computing for Managing Apparel and Garment Supply Chains—An Empirical Study of Implementation Frame Work. *Int. J. Comput. Sci. Issues* **2010**, *7*, 325–336.
49. Khairul-Akter, M.D.; Haq, U.N.; Islam, M.M.; Uddin, M.A. Textile-apparel manufacturing and material waste management in the circular economy: A conceptual model to achieve sustainable development goal (SDG) 12 for Bangladesh. *Clean. Environ. Syst.* **2022**, *4*, 100070. [CrossRef]
50. Moraga, G.; Huysveld, S.; Mathieux, F.; Blengini, G.A.; Alaerts, L.; Van-Acker, K.; de-Meester, S.; Dewulf, J. Circular economy indicators: What do they measure? *Resour. Conserv. Recycl.* **2019**, *146*, 452–461. [CrossRef] [PubMed]
51. Rossi, J.; Bianchini, A.; Guarnieri, P. Circular Economy Model Enhanced by Intelligent Assets from Industry 4.0: The Proposition of an Innovative Tool to Analyze Case Studies. *Sustainability* **2020**, *12*, 7147. [CrossRef]
52. Korhonen, J.; Honkasalo, A.; Seppälä, J. Circular economy: The concept and its limitations. *Ecol. Econ.* **2018**, *143*, 37–46. [CrossRef]
53. Ritzén, S.; Sandström, G.Ö. Barriers to the Circular Economy—Integration of Perspectives and Domains. *Procedia CIRP* **2017**, *64*, 7–12. [CrossRef]
54. Mendoza-Fong, J.R.; García-Alcaraz, J.L.; Macías, E.J.; Hernández, N.L.I.; Díaz-Reza, J.R.; Fernández, J.B. Role of Information and Communication Technology in Green Supply Chain Implementation and Companies' Performance. *Sustainability* **2018**, *10*, 1793. [CrossRef]
55. Fatimah, Y.A.; Govindan, K.; Murniningsih, R.; Setiawan, A. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *J. Clean. Prod.* **2020**, *269*, 122263. [CrossRef]
56. Nouinou, H.; Asadollahi-Yazdi, E.; Baret, I.; Nguyen, N.Q.; Terzi, M.; Ouazene, Y.; Yalaoui, F.; Kelly, R. Decision-making in the context of Industry 4.0: Evidence from the textile and clothing industry. *J. Clean. Prod.* **2023**, *391*, 136184. [CrossRef]
57. Abdul-Hamid, A.-Q.; Ali, M.H.; Tseng, M.-L.; Lan, S.; Kumar, M. Impending challenges on industry 4.0 in circular economy: Palm oil industry in Malaysia. *Comput. Oper. Res.* **2020**, *123*, 105052. [CrossRef]
58. Rajput, S.; Singh, S.P. Connecting circular economy and industry 4.0. *Int. J. Inf. Manag.* **2019**, *49*, 98–113. [CrossRef]
59. Stulga, P.; Whitfield, R.I.; Love, J.; Evans, D. Towards Sustainable Manufacturing with Industry 4.0: A Framework for the Textile Industry. *Proc. Des. Soc.* **2022**, *2*, 283–292. [CrossRef]
60. Hoekstra, A.Y. Water Footprint Assessment: Evolvement of a New Research Field. *Water Resour. Manag.* **2017**, *31*, 3061–3081. [CrossRef]
61. Singh, M.; Ahmed, S. IoT based smart water management systems: A systematic review. *Mater. Proc.* **2021**, *46*, 5211–5218. [CrossRef]
62. Park, K.T.; Kang, Y.T.; Yang, S.G.; Zhao, W.B.; Kang, Y.S.; Im, S.J.; Kim, D.H.; Choi, S.Y.; Noh, S.D. Cyber Physical Energy System for Saving Energy of the Dyeing Process with Industrial Internet of Things and Manufacturing Big Data. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2020**, *7*, 219–238. [CrossRef]
63. Barreto-Fereira, J.R.; Petit-Torres, E.E. Explanatory models of the process of technological innovation in the organizations. *Rev. Venez. Gerenc.* **2017**, *22*, 387–405.
64. Smetkowska, M.; Mrugalska, B. Using Six Sigma DMAIC to improve the quality of the production process: A case study. *Procedia—Soc. Behav. Sci.* **2018**, *238*, 590–596. [CrossRef]
65. Trimarjoko, A.; Purba, H.H.; Nindiani, A. Consistency of DMAIC Phases Implementation on Six Sigma Method in Manufacturing and Service Industry: A Literature Review. *Manag. Prod. Eng. Rev.* **2020**, *11*, 34–45.
66. Jamil, N.; Gholami, H.; Mat-Saman, M.Z.; Streimikiene, D.; Sharif, S.; Zakuan, N. DMAIC-based approach to sustainable value stream mapping: Towards a sustainable manufacturing system. *Econ. Res.—Ekon. Istraz.* **2020**, *33*, 331–360. [CrossRef]
67. Mesa, D.; Renda, G.; Gorkin, R.; Kuys, B.; Cook, S.M. Implementing a Design Thinking Approach to De-Risk the Digitalisation of Manufacturing SMEs. *Sustainability* **2022**, *14*, 14358. [CrossRef]
68. Heras-Rosas, C.; Herrera, J. Research Trends in Open Innovation and the Role of the University. *J. Open Innov. Technol. Mark. Complex.* **2021**, *7*, 29. [CrossRef]
69. Küsters, D.; Praß, N.; Gloy, Y.S. Textile Learning Factory 4.0—Preparing Germany's Textile Industry for the Digital Future. *Procedia Manuf.* **2017**, *9*, 214–221. [CrossRef]
70. Cordero-Guridi, J.d.J.; Cuautle-Gutierrez, L.; Alvarez-Tamayo, R.I.; Caballero-Morales, S.O. Design and Development of a I4.0 Engineering Education Laboratory with Virtual and Digital Technologies Based on ISO/IEC TR 23842-1 Standard Guidelines. *Appl. Sci.* **2022**, *12*, 5993. [CrossRef]
71. Turkyilmaz, A.; Shehab, E.; El-Thalji, I.; Ibraimov, N.; Dikhanbayeva, D.; Lukhmanov, Y.; Kabzhassarova, M.; Aitzhanova, M.; Yertayev, B.; Abilman, N. *COMMA 4.0—Comprehensive Maturity Assessment Model for Industry 4.0*; Nazarbayev University: Astana, Kazakhstan, 28 November 2021. Available online: https://comma4.net/ (accessed on 9 May 2023).
72. Lichblau, K.; Stich, V.; Bertenrath, R.; Blum, M.; Bleider, M.; Millack, A.; Katharina, S.; Schmitz, E.; Schröter, M. Industrie 4.0-Readiness. Available online: https://www.industrie40-readiness.de/ (accessed on 9 May 2023).
73. EDB Singapore. The Smart Industry Readiness Index (Siri)—Catalysing the Transformation of Manufacturing. Singapore Economic Development Board. Available online: https://www.edb.gov.sg/en/about-edb/media-releases-publications/advanced-manufacturing-release.html (accessed on 9 May 2023).
74. Henrique, D.; Freitas-Rentes, A.; Godinho-Filho, M.; Francisco-Esposposto, K. A new value stream mapping approach for healthcare environments. *Prod. Plan. Control* **2016**, *27*, 24–48. [CrossRef]

75. Mittal, S.; Romero, D.; Wuest, T. Towards a Smart Manufacturing Toolkit for SMEs. In Proceedings of the 15th IFIP International Conference on Product Lifecycle Management (PLM 2018): Product Lifecycle Management to Support Industry 4.0, Turin, Italy, 2–4 July 2018; Springer: Berlin/Heidelberg, Germany, 2018; pp. 476–487.
76. Zhang, Z.; He, T.; Zhu, M.; Sun, Z.; Shi, Q.; Zhu, J.; Dong, B.; Yuce, M.R.; Lee, C. Deep learning-enabled triboelectric smart socks for IoT-based gait analysis and VR applications. *NPJ Flex. Electron.* **2020**, *4*, 29. [CrossRef]
77. Radanliev, P.; De-Roure, D. New and emerging forms of data and technologies: Literature and bibliometric review. *Multimed. Tools Appl.* **2023**, *82*, 2887–2911. [CrossRef]
78. Radanliev, P.; De-Roure, D.; Nicolescu, R.; Huth, M.; Santos, O. Artificial Intelligence and the Internet of Things in Industry 4.0. *CCF Trans. Pervasive Comput. Interact.* **2021**, *3*, 329–338. [CrossRef]