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Operationalization of Critical Success Factors to Manage the Industry 4.0 Transformation of Manufacturing SMEs

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Abstract: As an increasing number of manufacturing small and medium enterprises (SMEs) tackle their digital transformation toward Industry 4.0, the need for a methodology to manage this transformation, tailored to their particular context, becomes apparent. Since recent studies have identified critical success factors (CSFs) for the Industry 4.0 transformation of manufacturing SMEs, this paper aims to operationalize these CSFs and propose an Industry 4.0 transformation management methodology. This research is based on an extensive literature review on CSFs for Industry 4.0 transformation, followed by a Delphi–Régnier survey with a panel of Industry 4.0 experts. For each CSF, specific actions to perform at different stages of the Industry 4.0 transformation were defined and validated by experts. Based on a proposed Industry 4.0 transformation process, not all CSFs have to be managed at every phase and step of the transformation process. Each CSF must be supported by different actions positioned within each Industry 4.0 transformation process step. The results of this research are particularly relevant for manufacturing SME managers and consultants managing Industry 4.0 transformation. By performing these actions, they can ensure the achievement of multiple CSFs during their digital transformation projects and, thus, ensure their success. This research combines the academic and professional domains by proposing a way for theoretical findings to be translated into clear actions. The proposed model allows all the actors involved in manufacturing SMEs' digital transformation projects to understand the actions needed to achieve a successful transformation.

Keywords: Industry 4.0; small- and medium-sized enterprises; manufacturing industry; critical success factor; project management

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1. Introduction

As we move toward evolving needs for manufactured goods and constant change in the global supply chain, manufacturing SMEs become increasingly relevant since they represent 99% of manufacturing companies in Canada and hire 84.7% of the manufacturing industry workforce [1,2]. Their past, present, and future performances highly affect the country's manufacturing industry and socioeconomic sustainability. Since they need to find ways to adapt and improve their performance and capabilities, one way to do so is by digitally transforming themselves toward Industry 4.0 practices [3,4]. Industry 4.0 is defined as "the 4th Industrial Revolution," which "represents a set of initiatives aimed at improving processes, products, and services by allowing decentralized decision-making based on real-time data acquisition through the introduction of digital technologies at every level of manufacturing companies and their supply chain" [3,5]. It is characterized by multiple technologies: collaborative robots, cyberphysical systems, big data, cloud computing, artificial intelligence, Internet-of-things, augmented reality, simulations, and 3D printing [4,5].

These technologies have been present in different industries for quite some time. However, the integration of multiple technology groups together, and the capacity to exploit data in real-time to improve manufacturing enterprises' performance and collaboration, is

one of the many characteristics that set Industry 4.0 apart as an industrial revolution [3,5–7]. Since Industry 4.0 is intimately linked to the exploitation of real-time data, many have defined Industry 4.0 as the digital transformation of the manufacturing industry [4,5,8–10].

Digital transformation is defined as the changes occurring in organizations, societies, and industries through digital technologies and information systems [11–14]. As such, digital transformation has been positioned as a way for enterprises to radically improve their performance and generate new value by implementing multiple technologies affecting their infrastructures, competencies, processes, and business models [12,13,15–18]. Because of these similitudes, Industry 4.0 and digital transformation have been used interchangeably through the literature when put into the context of the digital transformation of manufacturing companies.

Many studies have shown that multiple smaller projects are required to achieve the desired digital transformation. It is performed by introducing new technologies, exploiting existing technologies differently, introducing new processes, or changing the structure and business model of the company instead of a more traditional overhaul transformation that can take place through a few more significant projects [19–23]. It is especially true for the digital transformation of manufacturing SMEs [3,24]. SMEs prefer this approach as it allows them to counter many challenges and risks when deploying major digital technology projects [25–28].

Multiple studies have analyzed the challenges of digital transformation faced by manufacturing SMEs and identified potential solutions [25,29,30]. Some of the hurdles faced by manufacturing SMEs are elements such as data security; internal bureaucracies and regulations; lack of corporate culture for Industry 4.0 concepts; lack of skilled labor; lack of clarity, both on the economic benefits and on the vision of Industry 4.0, as well as on norms and standards; and overall inadequate infrastructure to support the implementation of these technologies [31]. Among the solutions to these hurdles, some authors propose Industry 4.0 maturity and readiness models [32–34]. Maturity models are tools used to assess the level of maturity of manufacturing SMEs within multiple dimensions relating to the level of technology they implement as well as their processes, system architecture, culture, strategy, and people [33,35,36]. Once an SME's maturity level is measured, these tools can identify the next step of its digital transformation and elements, such as management processes and architecture, that the SME must implement to reach the next maturity level [31,35].

Other studies have also proposed critical success factors for implementing Industry 4.0 technologies and principles [25,33,37,38]. These factors cover both technology and management elements that the manufacturers must possess to perform their digital transformations successfully. Overall, these studies provide generic guidelines to facilitate the digital transformation of manufacturing SMEs. However, they are highly conceptual and do not provide sufficient details to operationalize their recommendation in manufacturing SMEs.

Hence, this study aims to propose and validate a methodology to manage the digital transformation of manufacturing SMEs by operationalizing critical success factors. More specifically, the study aims to:

- Identify a list of actions associated with critical success factors to manage the digital transformation of manufacturing SMEs;
- Position these actions within the different phases of a manufacturing SME digital transformation process;
- Validate these actions with a panel of Industry 4.0 experts.

The remaining paper is divided into five sections: a literature review of the management of Industry 4.0 transformation within manufacturing SMEs and critical success factors, the research methodology, the findings, a discussion, and a conclusion.

2. Literature Review

To answer this question, we first covered recent studies on the digital transformation of manufacturing SMEs to understand better its characteristics and how it is managed. Re-

search papers on previously identified critical success factors for the digital transformation of manufacturing SMEs are then summarized.

2.1. Management of Industry 4.0 Transformation within Manufacturing SMEs

Studies on Industry 4.0 within manufacturing SMEs have gained steam in the past few years, and are considered a distinguished cluster of studies [10]. One of the reasons is that manufacturing SMEs possess different characteristics compared to large manufacturing companies, which affect their Industry 4.0 transformation processes, the challenges they face, and how they can overcome them. Since most manufacturing SMEs tend to have a flatter management structure and an absence of overarching bureaucracy, their managers and leaders can interact more efficiently and daily to make decisions affecting the company [39]. This result in a higher level of flexibility than larger companies have to react to external and internal events [40–43].

Unlike large companies, manufacturing SMEs do not always possess resources that can be dedicated entirely to new technology implementation projects or rapidly hiring resources specialized in the different technologies encompassed by Industry 4.0. As such, they tend to lack readily available resources and talents to manage and execute their digital transformation projects [22,28,44,45]. Contrary to large companies, who will define a long-term strategy and align short-term strategies to it, manufacturing SMEs tend to focus on short-term strategies and objectives and use their flexibility to review and realign their objectives and strategies based on new opportunities and challenges [5,28,46].

Finally, they lack processes and the organizational management maturity associated with large organizations [43,47]. As such, multiple studies, mainly based on case studies, have focused on how the characteristics of manufacturing SMEs impact their digital transformation, the challenges they encounter, the gain and opportunities Industry 4.0 will bring them, and the lessons learned after their transformation [5,10,33].

Other studies have tried to understand how manufacturing SMEs can approach the management of their digital transformation to Industry 4.0. Because they are short-sighted in terms of strategy and possess more flexibility than large companies, manufacturing SMEs prefer to establish small and rapidly attainable objectives for their Industry 4.0 transformations and use their flexibility and adaptiveness to navigate through their digital transformations, adjusting their portfolio of projects as they progress [20,48]. Because of these characteristics, most manufacturing SMEs will achieve digital transformation through a set of small technology implementation projects to minimize the impact on their organizations in terms of the process changes needed to support the new technology [22,25,49,50].

Larger companies tend to approach digital transformation by implementing a sizeable general architecture, implementing systems to acquire as much data as possible, and then implementing data valorization projects to exploit this data [51–53]. This means that large organizations will implement multiple data acquisition technologies, which need to be supported by a more significant IT infrastructure (faster network, bigger server, more compute power), be it on-premises or cloud-based [52]. To support these growing needs for IT infrastructure, large organizations must either build or collaborate with big data centers. The larger the organization, the exponentially bigger the quantity of data it will acquire, and the larger the data center needed. These past few years, concerns regarding the rise in new data center construction and their effects on the environment through energy consumption have grown [54]. This growing concern led researchers to study the sustainability and energy consumption of big data centers fuelled by the digital transformation of large organizations [55]. On the other hand, manufacturing SMEs will first implement technologies that their current IT infrastructure can support to minimize the complexity of their project and hasten their return on investment, resulting in a more sustainable approach to digital transformation [30,56].

Finally, some studies have shown that, in order to manage and execute digital transformation through this set of iterative projects, some SMEs will define and implement basic project management and portfolio management tools and processes [21,57]. These

tools and processes tend to evolve over time as the manufacturing SMEs gain maturity and complete more and more projects [21]. The manufacturing SME will also undergo multiple small organizational changes over time to support their digital transformations by adopting new processes, hiring new resources, or changing the organizational chart and hierarchy as needed [50].

2.2. Critical Success Factors for Industry 4.0 Transformation

Critical success factors (CSFs) have been thoroughly studied and translated into actions within multiple contexts, such as the implementation of ERP systems in manufacturing companies [58]. More recently, multiple researchers have investigated the critical success factors for the Industry 4.0 transformation of manufacturing SMEs. These critical success factors were identified through structured literature reviews [37,38,59,60] as well as through Delphi methodologies with panels of experts [25,58] and case studies [61]. Moeuf, Lamouri, Pellerin, Tamayo-Giraldo, Tobon-Valencia, and Eburdy [25] identified a total of ten critical success factors through a Delphi study with experts in digital transformation in manufacturing SMEs, ranging from the importance of "conducting a study prior to embarking upon any Industry 4.0 project" to the importance of employee training. Sony and Naik [59] also identified ten critical success factors through a literature review to support implementing cyberphysical systems. Finally, Françoise, Bourgault, and Pellerin [58] operationalized 13 critical success factors for managing ERP implementation projects. Overall, when looking at overlapping CSFs identified for both digital transformation projects and within the context of manufacturing SMEs, we can summarize them within the ten following CSFs.

Align Industry 4.0 strategy to business strategy

Industry 4.0 does not only focus on manufacturing operations or supply chain management; it encompasses every aspect of the organization [22,62]. As such, the transition to Industry 4.0 starts with defining short-, medium-, and long-term objectives. These objectives must support the short-, medium-, and long-term business strategy objectives. It is thus essential to ensure that Industry 4.0 projects and strategies are correctly aligned with the business strategy at every step of the Industry 4.0 transformation [38,59].

Leadership

The impact of management leadership on organizational performance and the success of transformative projects has been studied intensely [63]. It is no surprise to see that, for a successful digital transformation, a manufacturing SME must involve company leaders in the process to ensure the support of the high management of the company and to appoint an Industry 4.0 champion to support the digital transformation of the company [25,37,58].

Alignment along a hierarchical line

SMEs tend to have a short hierarchy where leaders are very close to their employees [47]. This proximity facilitates the Industry 4.0 transformation of the organization by making the objectives and issues clearer and more transparent, making it possible to motivate the employees and limit change resistance. It also promotes communication between employees [25]. As such, it is essential to align the objectives of manufacturing SMEs vertically and horizontally to ensure the success of the Industry 4.0 transformation.

Conduct a study prior to Industry 4.0 projects

Conducting a study on company processes, performance, architecture, and tools allows manufacturing SMEs to properly assess the root cause of their issues and better identify the potential gains they could achieve from an Industry 4.0 transformation [25,38,59].

Communication management

Communication is critical in any project and takes different forms based on the company. As such, an effective communication strategy for the Industry 4.0 transformation of the company at every level is essential to ensure employees' acceptance of the transformation process while also facilitating coordination between the Industry 4.0 champion and the management team [25,58].

Teamwork and team composition

For the Industry 4.0 transformation to succeed, the manufacturing SMEs need to implement a transformation team composed of the right employees and consultants with the right skill sets [25,58]. Teamwork has been identified as one of the main critical success factors in project management, including digital transformation projects [64,65].

Employee training and knowledge management

As manufacturing SMEs implement new technological solutions that will affect their employees' internal processes and day-to-day work, it is necessary for a company to properly train the employees on how to use and support the new solutions [25,38,58,59]. The manufacturing company must also document how to use and support the implemented solutions properly and put in place knowledge-retention processes and tools to facilitate the knowledge management of these solutions [25,38].

Organizational culture and change management

The implementation of Industry 4.0 affects the organization's structures due to its integration at every level of the organization [66,67]. These changes can become radical changes that need to be addressed and managed. Change management at different stages of the transformation and through each project must be considered to ensure employee participation and reduce resistance [25,58,59].

Project management

Industry 4.0 implementation should be executed in a series of well-planned and strategically scheduled projects for its success [5,21,25,68]. It is essential to properly manage these projects using the right set of project management tools, processes, and approaches [25,59].

Continuous improvement strategy

Moeuf, Lamouri, Pellerin, Tamayo-Giraldo, Tobon-Valencia, and Eburdy [25] have shown that "having a continuous improvement strategy promotes agility among employees and their ability to adopt new tools and processes." Considering that the Industry 4.0 transformation of manufacturing SMEs is performed through a succession of multiple projects [21,25,68], aligning the Industry 4.0 transformation processes with the continuous improvement strategy has been shown to facilitate the adoption of new technologies used by employees and ensure the alignment of the Industry 4.0 project with the business strategy [22,25,38,69].

2.3. Research Limitations

The list of critical success factors presented above provides essential elements to guide manufacturing SME managers and consultants to identify areas where intervention is needed during an Industry 4.0 transformation. However, these factors are generic and are rarely followed by actions practitioners can perform to implement and support them.

In order to manage its Industry 4.0 transformation, the manufacturing SME must operationalize these CSFs. It needs to perform actions at different steps and phases of its Industry 4.0 transformation process to implement and support them. The identification of actions to manage and support CSFs has been researched before in multiple contexts relating to digital technologies: ERP implementation projects [58], IT governance performance [70], and the implementation of supply chain information systems [71]. However, these studies do not address the context of Industry 4.0 transformation within manufacturing SMEs. As we discussed earlier, the context of Industry 4.0 transformation in manufacturing SMEs involves a succession of small, short-term iterative projects. As such, manufacturing SMEs must manage an ever-changing portfolio of projects aligned with their Industry 4.0 vision and strategic objectives. Past studies aimed at operationalizing digital projects in the manufacturing industry focus mainly on single, large, transformative projects, such as implementing an ERP or a supply chain information system. They identified actions to support CSFs within these single major projects. The actions also stop at the end of each project, without any actions that could encompass an iterative process. Even when these studies produced lists of actions to support each CSF, they did not indicate at which steps and phases of their respective implementation methodologies these actions took place. As such, it would be challenging for both researchers and practitioners to transpose these

actions as is to manage the Industry 4.0 transformation of manufacturing SMEs. To fill this gap, this study aims to propose and validate a methodology to manage the Industry 4.0 transformation of manufacturing SMEs through the operationalization of CSFs.

3. General Framework

To identify and position the actions, we created a general framework, shown in Figure 1, highlighting the relation between the actions, critical success factors, and phases and steps for managing the Industry 4.0 transformation of manufacturing SMEs. This framework proposes that knowledge about the CSFs of Industry 4.0 transformation generates actions at different steps and phases of the Industry 4.0 transformation process that will make it possible to establish, support, and manage these CSFs. It also proposes that different actions are required for each CSF depending on the step and phase of the transformation process.

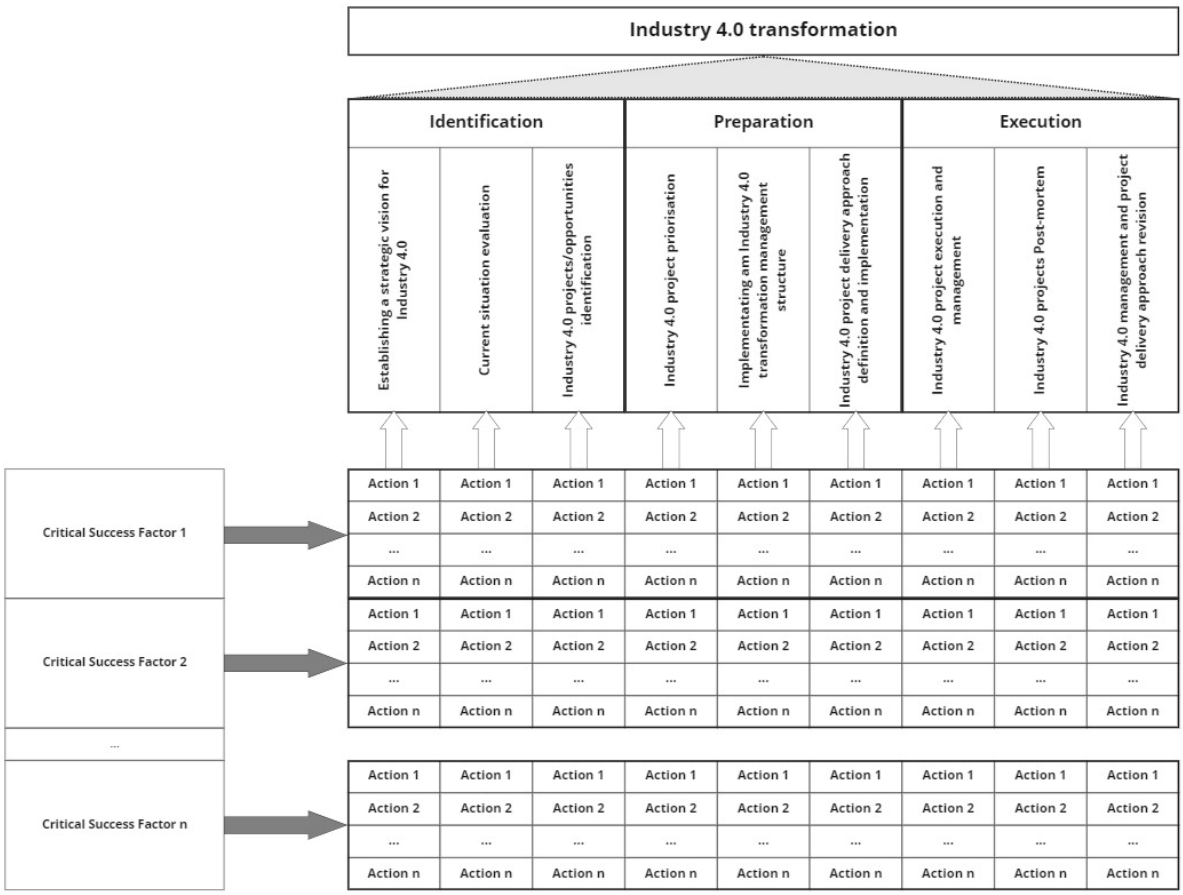

Figure 1. Proposed framework.

We divided the Industry 4.0 transformation management process into three phases and nine steps based on past case studies and Delphi research detailing the phases, steps, and overall best practices used by manufacturing SMEs to manage their Industry 4.0 transformations [19,21,22,25,50,61]. These phases allow manufacturing SMEs to identify potential Industry 4.0 projects able to solve business issues and support their strategic visions. They also allow the SMEs to prepare themselves to launch their Industry 4.0 transformations by implementing the tools, processes, and resources needed to execute and manage their transformations. Finally, they allow SMEs to execute their transformations in an iterative matter. The three phases are the following: **Identification**, **Preparation**, and **Execution**.

In the **Identification phase,** the manufacturing SME identifies potential Industry 4.0 projects before starting its Industry 4.0 transformation. Moeuf, Lamouri, Pellerin, Tamayo-

Giraldo, Tobon-Valencia, and Eburdy [25] identified that, for an Industry 4.0 transformation to be successful, the manufacturing SME needed to conduct a study to identify Industry 4.0 projects that could support its Industry 4.0 vision and strategy. The manufacturing SME has to create an Industry 4.0 vision aligned with its business strategy [25,37,59], assess the current performance of its processes and technologies [25,37,38], and determine its capacity to deliver its Industry 4.0 vision and projects [37,59,64].

Within this phase, the three following steps are proposed:

- **Establishing a strategic vision for Industry 4.0:** The manufacturing SME must first properly define its Industry 4.0 vision and position it as part of its business strategy. The SME will define strategic objectives that its Industry 4.0 strategy will support and position them in time [25,37,59].
- **Current situation evaluation:** The manufacturing SME needs to evaluate its current situation regarding digitalization. It must evaluate its processes, performance, current technology architecture, resources, and capabilities [25,37,38].
- **Industry 4.0 project/opportunity identification:** Based on its vision and current situation, the manufacturing SME can identify potential Industry 4.0 projects that will enhance its position to achieve its strategic goals [57,72,73].

Once the manufacturing SME Industry 4.0 vision and list of projects are determined, the manufacturing SME has to provide itself with the means to manage and execute this transformation. To do so, it needs to:

- Prioritize its Industry 4.0 projects to create an Industry 4.0 roadmap based on its objectives and capacity [57,60,74,75];
- Define the tools, governance, and processes to manage its transformation [21,57,76];
- Define the processes and tools it will use to manage and deliver each project [21,57];
- Allocate resources to the transformation projects [25,38,59].

We then encompass these elements into the **Preparation phase** and divide them into three steps:

- **Industry 4.0 project prioritization:** The manufacturing SME prioritizes its Industry 4.0 projects into a project portfolio based on its strategic vision and current situation to create an Industry 4.0 transformation roadmap [57,60,74,75].
- **Implementing an Industry 4.0 transformation management structure:** The manufacturing SME defines and implements the governance, processes, and tools that will allow it to manage and support its Industry 4.0 transformation process [21,57,76].
- **Implementing an Industry 4.0 project delivery approach:** The manufacturing SME defines and implements the processes, tools, and teams to execute and manage the Industry 4.0 projects [21,57].

Once the projects are identified and aligned, and the manufacturing SMEs provide themselves with the means to deliver them, they can start the **Execution phase**. The execution phase starts as an iterative process in which the manufacturing SME delivers the project, assesses what it could have done better, revises its processes and tools, and starts again with another project [21,25,50]. As discussed in the literature review, manufacturing SMEs will approach digital transformation through iterative projects. It is then essential to divide this phase into steps that can represent this iterative approach. Through this phase, the manufacturing SME can constantly improve itself in managing and delivering its Industry 4.0 transformation [50,68], revise its Industry 4.0 project portfolio [21,38], and ensure that the company steadily adopts the changes brought by the technologies and processes [50,76,77]. This iterative process is again divided into three steps:

- **Industry 4.0 project execution and management:** The manufacturing SME executes and manages its Industry 4.0 projects following the structure and approach it defined and put in place [21,57].
- **Industry 4.0 project post-mortem:** The manufacturing SME reviews its Industry 4.0 projects by analyzing if their objectives were met, if issues happened during the project,

how it solved them, what it could have done to prevent them, and what it should do better or differently on the following projects [21,78].

- **Industry 4.0 management and project delivery approach revision**: The manufacturing SME revises and implements changes to its management structure for Industry 4.0 transformation and its project delivery approach based on the project post-mortem analysis and the impact of the Industry 4.0 projects [21,38,50,76,77].

Within each phase, we will identify a list of actions to manage the Industry 4.0 transformation of manufacturing SMEs influenced by well-established critical success factors [25,38,59].

This framework will also serve as the foundation of a methodology relevant to practitioners, who can easily integrate these actions within their own project management processes. This framework makes it possible to identify the critical success factors that need to be supported and managed through actions at each step. It is worth mentioning that this framework will also allow us to identify if all CSFs need to be managed and supported at each step of the transformation process based on the presence or lack of actions identified.

4. Research Methodology

To identify and position the actions, we conducted an extensive literature review on CSFs, focusing on the Industry 4.0 transformation process. We then validated the actions and their positions within the process through a Delphi–Régnier survey with a panel of Industry 4.0 experts. As such, specific actions to perform at different stages of the Industry 4.0 transformation for each CSF were defined and validated by experts. This methodology is explained in further detail in the following subsections.

4.1. The Delphi Methodology

The Delphi methodology aims to obtain and organize the opinions of a panel of experts on a particular subject. It can be used to explore complex subjects or to develop models. This methodology is recognized for its ability to bring forward empirical evidence led by the consensus or dissensus of a group's opinion on a subject. It is defined as "an iterative process used to collect and distill expert judgments using a series of questionnaires" [79–81]. This method is typically divided into expert recruitment and multi-time data collection processes, called "iterations." Each iteration refines the opinions and data collected in the previous iteration and returns the responses to the experts [80]. Comparing the opinions of multiple experts on our subject will ensure we achieve our research objectives. The iterative process stops when the research team considers its question answered and its objectives met [81].

To minimize the risk of bias and ensure the experts' participation, they must remain anonymous to each other, having access only to the other participants' answers at the end of each iteration. Direct communication between the experts is forbidden. It ensures an honest opinion on the element of the questionnaire and that the opinions of other experts do not influence their own opinions at the time of answer.

Skulmoski et al. (2007) noted that the Delphi methodology is flexible. Many adaptations on how to operationalize it have been made in past research, with the two most variable elements being the number of iterations and the methods used to collect data. Given our research topic and the need to facilitate our data collection and analysis process, the Delphi method was combined with Régnier's abacus to create our exploratory data collection method. This method has been used multiple times to collect and summarize expert opinions on Industry 4.0 technologies, risks, opportunities, and impacts on manufacturing SMEs [25,82].

4.2. The Abacus of Régnier

The abacus of Régnier is a technique that uses a panel of colours to collect experts' opinions about precise statements. Its main advantage is the speed at which it can summarize opinions thanks to its colourful visualization of results that facilitate the identification

of consensus and dissensus in the experts' opinions on each statement [83]. The experts must choose between seven colours to express their opinion:

- Green: Completely agree with the statement;
- Light green: Somewhat agree with the statement;
- Yellow: Mixed opinion on the statement;
- Light red: Somewhat disagree with the statement;
- Red: Completely disagree with the statement;
- White: Cannot answer;
- Black: Do not want to answer.

The experts' opinions appear in a colourful visualization synthetizing the experts' consensus and dissensus on each statement, facilitating its analysis. This study used the platform Color Insight (http://colorinsight.fr/ accessed on 31 May 2022) to create the questionnaires, distribute them to experts, collect the answers, and generate colour visualization ready for analysis.

The combination of these two methods and techniques will be referred to by the term "Delphi–Régnier" in this article.

4.3. Selection of Experts

The Delphi methodology's main characteristic is that it consults a group of experts, often described as a "panel of experts," where the "expert" is defined as an "actor with recognized skills in a field and responsible for contributing to the elaboration of a judgment" [79,83]. As such, the constitution of the expert panel must be based on the three following criteria:

1. The experts' experience;
2. Their familiarity with the research subject;
3. Their expertise in the research subject.

To include the perspective of multiple actors with experience in the subject, we created three different categories of experts. For each category, the expert must meet the following criteria:

1. Must have analyzed, managed, or executed digital transformation projects over the past three years;
2. Must have worked for, or in collaboration, with manufacturing SMEs on digital transformation projects;
3. Must have been involved in the starting phase of digital transformation within one or multiple manufacturing SMEs.

The first criterion ensures that the expert has firsthand experience with digital transformation projects. The second criterion ensures that their experience and expertise have been developed within the context of manufacturing SMEs, the main subject of our study. Finally, the third criterion ensures that their experience and expertise are related to the digital transformation management aspect instead of the technical aspects. With these criteria, we ensured that our experts could provide an informed opinion on actions to manage the digital transformation of manufacturing SMEs.

The experts were divided into three categories, including practitioners and academic perspectives. They are the following:

- **Industrial Manager**: Member of the high management or a project/program manager of a manufacturing SME;
- **Academic**: Researcher or university professor who has conducted research on the digital transformation of manufacturing SMEs;
- **Independent Consultant**: Consultant and expert in digital transformation who has supported manufacturing SMEs in managing their digital transformations.

The size of the experts' panel can vary depending on the research. Mitchell [84] and Ashton [85] suggest that around 10 and 11 experts participate in a Delphi Study. Recent

studies using the Delphi-Régnier methodology were based on a panel composed of around twenty experts [25,82,86]. For our study, our panel was composed of 19 experts distributed as follows: six industrials, six academics, and seven independent consultants.

4.4. Survey Creation

The initial questionnaire was created to validate actions to support CSFs at each phase and step of the manufacturing SME Industry 4.0 transformation process. We identified multiple actions for each step and critical success factor and asked the panel of experts to comment on the actions and their positions.

The list of actions used in the initial questionnaire was identified following a literature review of Industry 4.0 management in manufacturing SME case studies [21,22,61] and from past research on similar critical success factors for the project management of IT and ERP projects [58,87]. Following the model in Figure 1, we positioned each action under different steps and used the Delphi method to validate or invalidate the position of these actions within the model.

The initial questionnaire was validated by a small panel of integrator experts from the Center of Industrial Expertise of Montreal, who work on supporting digital transformation projects in manufacturing SMEs. This small panel of experts had minimal experience in Delphi surveys but several years of experience working with industrial managers and consultants in digital transformation. They identified potential misinterpretations of the questions and suggested ways to make it easier for industrial and integrator experts to interpret them.

4.5. Iteration Structure

The experts first answered a questionnaire of 67 statements using the Color Insight platform. The statements are shown in Appendix A. They gave their opinion by selecting different colours from Régnier's abacus. The experts were also asked to comment on their answers to justify them or add more nuance to the statements. They were also invited to submit additional statements and opinions at the end of each section of the questionnaire.

Once the first round of statements was completed, the research team reviewed and analyzed the votes and comments. Based on the results and comments, a second questionnaire of 19 statements, provided in Appendix B, was created and submitted to the participants, who answered the first questionnaire with both the results from their first questionnaire and a summary of their comments, consensus, dissensus, and suggestions.

Complementary information necessary to interpret the experts' opinions on the first questionnaire was gathered during this second iteration. Following the analysis of this information, the research team ended the study. All 19 experts participated in both rounds of the study.

As shown in Appendices C and D, the Color Insight platform generated an item matrix from the expert votes on each statement. This matrix of items classified the statements from the "most agreed to" to the "least agreed to," helping us visualize and analyze the answers. The dissensus items appear in the middle of the matrix. The matrix was automatically generated with the "classic mode" of the platform Color Insight, and the colours were weighted from 5 for green (completely agreed with) to 1 for red (completely disagree with). Based on past evaluation thresholds in similar research [25,57,82], it was decided that the experts reached a consensus when 60% of their responses agreed (green) or disagreed (red) with the statement.

5. Findings and Discussion

During the first iteration of the study, the research team prepared the questions to validate actions to support the critical success factors of the Industry 4.0 transformation of manufacturing SMEs. For the second round, the research team prepared a second set of questions to clarify the experts' answers on two elements: The Industry 4.0 champion and

the SMEs' capacity to manage and execute their Industry 4.0 transformation. After analysis of all the data, we summarized the experts' opinions into three categories:

- Steps and actions to manage the Industry 4.0 transformation;
- Dependence on the context of individual manufacturing SMEs;
- Managing the transformation through an iterative process.

The following subsection summarizes the experts' opinions and comments supporting these categories. To reference the statement presented to the experts, we used the following formula: QX-IY, where X references the questionnaire and Y references the item. For example, the reference Q1-I1.4 references Item 1.4 in the first questionnaire, which would be "Designate a Digital Transformation Champion." The questionnaires can be referred to in Appendices A and B.

5.1. Steps and Actions to Manage Industry 4.0 Transformation

This section synthesized the experts' answers and comments at each step presented in Figure 1.

5.1.1. Establishing a Strategic Vision for Industry 4.0 (Q1-1.1 to Q1-1.9, Q2-1.1 to Q2-1.13)

The experts' answers allowed us to verify the actions needed to align the Industry 4.0 strategy with the manufacturing SME business strategy. Even if the experts disagreed on reviewing the entire business strategy to consider digital technology, they indicated that it was necessary for the SME to align its Industry 4.0 objectives with the business strategy and to identify the business objectives that the Industry 4.0 strategy will support. An IT architecture vision must also be defined to support the company's digital transformation.

To ensure that the strategy and vision are communicated and agreed upon at the different levels of the hierarchical line, the strategy should be communicated to the manager of every department and business unit. The experts also indicated that the company should obtain a commitment from the managers and directors of these departments to support the Industry 4.0 transformation. Experts suggested that "a steering committee should be created "at this step.

They also indicated that naming an Industry 4.0 champion was necessary for our experts as it ensures that a leader will oversee the Industry 4.0 transformation. However, the experts disagreed on the champion being part of the high management team of the company or the company's CEO. Instead, they indicated that the Industry 4.0 champion should be an official position given to a manager under the SME high management or CEO. The champion should possess prior experience in IT or digital transformation projects and be responsible for educating the SME's management and employees on the principles and technologies of Industry 4.0. Finally, the champion should be given the authority to identify and prioritize the Industry 4.0 projects and implement governance to manage the Industry 4.0 transformation process.

5.1.2. Current Situation Evaluation (Q1-2.1 to Q1-2.5, Q2-I2.1 to Q2-I2.5)

The experts indicated that the manufacturing SME should evaluate the performance of critical processes and technologies and evaluate its current IT infrastructure and business architecture. They also suggested that the SME evaluate its capacity to execute and manage its Industry 4.0 transformation. To do so, it should assess its financial abilities, its employees' expertise and experience in Industry 4.0 technologies and projects, its internal project management and continuous improvement processes, its employees' and managers' resistance to change, and any external help available.

Finally, the experts agreed that the SME should involve the company's management and key employees in the evaluation process and communicate the evaluation results to the company's management.

5.1.3. Industry 4.0 Projects/Opportunities Identification (Q1-I3.1 to Q1-I3.6)

Once the Industry 4.0 strategic visions and objectives are established and the current situation of the manufacturing SME is assessed, it is now possible to identify Industry 4.0 projects that could fill the gap between the current situation and the vision, leading to the creation of an Industry 4.0 projects portfolio. The experts indicated that the Industry 4.0 project objectives needed to be aligned with the SME's Industry 4.0 strategy and business strategy objectives. Industry 4.0 projects should be able to solve business and operations issues, ensuring that some projects fit into the continuous improvement strategy of the SME. While identifying the different Industry 4.0 projects, the experts indicated that IT infrastructure and architecture projects supporting the Industry 4.0 projects should also be identified.

In this step, the SME should define each project's scope and objectives and assess its technology prerequisites, schedule, budget, and potential risks. The SME should identify the resources and expertise needed for each project at this stage. Finally, many experts suggested that a steering committee should be involved in identifying and validating the Industry 4.0 project portfolio.

5.1.4. Industry 4.0 Projects Prioritization (Q1-I4.1 to Q1-I4.6, Q2-I1.9, Q2-I2.6)

When prioritizing the project portfolio, the experts indicated that many elements should be considered: the priority of the strategic objectives, the access to financial resources, the technology prerequisite between projects, and the overall capacity of the SME to execute and manage their projects. Some suggested that the SME should first identify *quick-win* projects to gain their employees' and management's confidence in the transformation, that a steering committee should be involved in the prioritization process, and that the champion should manage this process. Some experts also suggested tools and techniques that support the prioritization process, such as the impact vs. effort matrix and Industry 4.0 roadmaps.

Finally, the experts indicated that the prioritization should be validated with the company's high management team and communicated to managers and employees.

5.1.5. Implementing an Industry 4.0 Transformation Management Structure (Q1-I5.1 to Q1-I5.4, Q2-I1.10)

The Industry 4.0 management structure is defined by a set of processes used to manage and monitor the Industry 4.0 transformation. The experts considered that the champion should have the authority to implement the required management and governance structure. The experts also found it necessary to implement a communication management plan and a formal change management process.

When asked about what should be added to these elements, the experts indicated that a steering committee should be part of the governance structure to ensure the commitment of the other department of the company. They also suggested that SMEs should manage the changes generated by the Industry 4.0 projects and perform organizational changes if needed. Finally, the experts suggested that the SME implement tools and processes to manage the support function (helpdesk), continuously improve the new solutions, and identify and gather new Industry 4.0 project proposals.

5.1.6. Implementing an Industry 4.0 Project Delivery Approach (Q1-I6.1 to Q1-I6.12)

In parallel with establishing the Industry 4.0 management structure, the manufacturing SME must decide how it will deliver its projects. The expert panel indicated that an Industry 4.0 project manager role should be created. Furthermore, internal resources with the right expertise should be identified and allocated to the projects. If not available within the company, they should be hired as new employees or external integrators and consultants. They also indicated that the roles and responsibilities of each team member and the project stakeholder should be identified and documented to enhance teamwork. The SME should also implement tools and processes to facilitate communication coordination and collaboration between the team members.

To ensure that the project management process is effective, the experts indicated that the SME should introduce tools and processes to plan, monitor, and manage the project's schedule, budget, and risk plan. The inclusion of a communication plan for each project was also highly recommended.

As for the delivery approach itself, the experts did not agree on which approach to use. Some suggested using an iterative and agile approach, involving a quick succession of proof-of-concept, prototype, validation, and deployment phases for smaller projects. Others preferred a cascade approach for larger projects. Overall, they commented that the approach for delivering projects depends on the specific characteristics of the projects considered.

5.1.7. Industry 4.0 Projects Execution and Management (Q1-I7.1 to Q1-I7.9)

To ensure that the Industry 4.0 projects are appropriately managed and executed, the experts indicated that regular follow-up on the progress of the projects should be performed with the project managers and the Industry 4.0 champion as per the established governance process. The experts also highlighted that the budget and schedule should be revised and adapted based on the project's progress. The project manager should ensure coordination, communication, and collaboration between the team members and the project stakeholders during the projects.

Knowledge management was also a considerable concern for the experts. They suggested that changes to the IT infrastructure and architecture and the new processes and technologies implemented within the Industry 4.0 projects should be adequately documented. A support process for the technology users should be implemented and documented. Of course, they also suggested creating a training program and documentation for the employees on the new processes and technologies implemented.

The experts disagreed on the need to validate the project stakeholders' choice of the selected Industry 4.0 technologies during project execution. As some experts mentioned, if the project scope was defined as the "implementation of System X", the technology validation or feasibility analysis should be performed before the project starts. However, if the project scope is defined as a function, for example, "measuring the efficiency of our CNC machines", then the technology used to perform the function must be identified and validated with the stakeholders in the first phases of the project before being deployed.

5.1.8. Industry 4.0 Projects Post-Mortem (Q1-I8.1 to Q1-I8.3)

The experts insisted that a post-mortem at the end of each Industry 4.0 project must be performed. They indicated that the project's stakeholders, the project team, and the employees and managers of the department in which the Industry 4.0 project took place should all be involved. They also indicated that the post-mortem activity was also the right moment to evaluate how the Industry 4.0 management structure and delivery approach positively or negatively affected the project.

In order to properly perform the post-mortem, the experts suggested evaluating the following for each project:

- The critical success factor of each Industry 4.0 project;
- The gap between the estimated and actual budget and schedule;
- The presence or absence of internal expertise needed for the project;
- The relationship with external partners and suppliers on the project;
- The performance of the project team members as per their roles and responsibilities.

5.1.9. Industry 4.0 Management and Project Delivery Approach Revision (Q1-I9.1 to Q1-I10.5)

Based on the results of the post-mortem, potential revision to the Industry 4.0 management structure and project delivery approach could be needed. As such, the experts indicated that the manufacturing SME should revise its communication plan, governance, project management tools, and processes and suggested revising the role and respon-

sibilities of the project team members, all of them on a necessity basis instead of on a systematic basis.

The experts also suggested it was the right moment to evaluate new Industry 4.0 project proposals and revise the project portfolio based on the completed project results. The experts also insisted that a proper technological survey should be included when reviewing the project portfolio and roadmap.

With each change to the tools, processes, and governance structure, proper project team training might also be necessary. The experts indicated that with these revisions, some organizational changes, such as revisions to the organizational chart and adding new tools and processes, might be needed and should be identified and managed to ensure that the Industry 4.0 transformation is adequately supported. Finally, the experts indicated that changes and revisions should be validated by the stakeholder, communicated to the employees and managers, and documented.

5.2. Dependence on the Context of Individual Manufacturing SMEs

The experts also commented on the overall management processes and actions needed to manage the Industry 4.0 transformation of manufacturing SMEs. One recurring theme was how each manufacturing SME's context differed from another and could affect the presence and position of actions needed to support the CSF. Even if they highly suggested that the Industry 4.0 champion should not be the company's CEO, multiple experts claimed that, for smaller SMEs with a flat hierarchy, the CEO could indeed act as the champion. In other contexts, the champion could also be the project manager or supervise them.

Another element dependent on the context of the SME is the definition of the scope of the Industry 4.0 projects and the delivery approach to be used. We already discussed this element in Section 5.1.6. In addition, based on the experts' comments, the scope could be defined in any way that suits the manufacturing SME's objectives. The delivery approach could be created based on existing project management processes. It also applies to the project prioritization process. Even if the experts indicated multiple elements to analyze to help prioritization, one SME could decide to prioritize based on only a subset of these mentioned elements. Another SME could decide to prioritize based on other elements.

In summary, even if the experts indicated multiple actions that a manufacturing SME should perform, how it interprets these actions and which actions it will perform will depend on its context.

5.3. Managing the Transformation through an Iterative Process

Multiple experts mentioned that the Industry 4.0 transformation should be an iterative process. How to manage it and the actions needed to achieve its critical success factors would change over time. This led multiple experts to suggest that the SME should execute them more simply and then use the revision process to expand it. For example, the steering committee created at the beginning of the transformation could include only the champion, the CEO, and the director of operations. However, the steering committee could be revised to include other departments and stakeholders over time. The same recommendation could be applied to the project management tools and processes: The SME could start with essential tools like a high-level schedule and budget and revise them to include more advanced project management tools, processes, and techniques, such as earned value calculation, in subsequent projects.

Some experts also mentioned that manufacturing SMEs should give themselves the tools, processes, and means to explore solutions through a succession of small and fast proof-of-concept projects. It would allow them to better understand Industry 4.0 technologies, gain maturity, and identify how they could support their business strategies. Unfortunately, the experts did not provide any specific practical actions on that matter. They commented that the elements put in place by the identified actions of this research should reflect an iterative process.

6. Main Results and Limitations

This research's main objective was to develop a methodology to manage manufacturing SME Industry 4.0 transformation plans through the operationalization of CSFs. Based on comments from and the results of a Delphi–Régnier study with a panel of experts in the digital transformation of manufacturing SMEs, we identified specific actions to be performed at different phases and steps of the Industry 4.0 management process, as seen in Tables 1–3. Each action has been positioned within its respective steps and phase.

As we can see, different actions are necessary to support the CSFs at the different steps and phases of the Industry 4.0 transformation management process, and not all the CSFs are present within each step. As seen in Table 1, the actions in the identification phases are mainly used to ensure the alignment of the Industry 4.0 strategy with the business strategy and to establish the leadership needed to manage the transformation. They are also used to align the hierarchical line of the company, ensuring the Industry 4.0 projects are appropriately defined as ways to improve the processes and operations of the company and ensuring that the strategy and the list of projects are appropriately communicated at the different levels of the company.

Table 1. Actions to support CSF in the identification phase.

Identification Phase	Critical Success Factors	Actions
Establishing a strategic vision for Industry 4.0	Align Industry 4.0 strategy to business strategy	• Review the strategic financial and operational objectives of the company. • Identify the strategic financial and operational objectives that the Industry 4.0 strategy will support. • Define funding and granting strategy to support the Industry 4.0 transformation. • Define, as part of the Industry 4.0 vision, an IT architecture and infrastructure.
	Leadership	• Appoint an Industry 4.0 champion who will answer to the high management of the manufacturing SME. • Ensure that the Industry 4.0 champion is familiar with the concept, technologies, and principles of Industry 4.0. • Ensure that the Industry 4.0 champion possesses experience in digital transformation and manufacturing. • Determine the level of authority of the Industry 4.0 champion.
	Alignment along hierarchical line	• Create a steering committee tasked with overlooking the Industry 4.0 transformation. • Validate the digital transformation strategy with the management of all the departments and business units of the manufacturing SME. • Obtain a commitment to support the Industry 4.0 transformation strategy from the directors and managers of the SME.
	Communication management	• Communicate the Industry 4.0 strategic vision to all of the employees and managers of the manufacturing SMEs.
Current situation evaluation	Conduct a study prior to Industry 4.0 projects	• Execute a diagnosis of the critical business process and technologies targeted by the Industry 4.0 strategic vision. • Assess the current IT infrastructure and architecture. • Assess the company's financial means. • Assess the current project management and continuous improvement process. • Assess the employees' and managers' level of resistance to change toward Industry 4.0. • Assess the employees' expertise and experience on Industry 4.0 projects and technologies.
	Alignment along hierarchical line	• Involve the management of the different departments and business units in the evaluation process. • Involve key employees in the evaluation process.
	Communication management	• Communicate the results of the evaluation with the management of the company.

Table 1. *Cont.*

Identification Phase	Critical Success Factors	Actions
Industry 4.0 project/opportunity identification	Align Industry 4.0 strategy to business strategy	• Identify the Industry 4.0 projects based on the current situation analysis and the Industry 4.0 strategic vision. • Align the Industry 4.0 projects' objectives with the business strategy and Industry 4.0 strategy.
	Alignment along hierarchical line	• Ensure that the steering committee is involved in the identification process.
	Project management	• For each project, define the scope and assess the prerequisites, schedule, budget, and potential risks. • For each Industry 4.0 project, assess the expertise and resources needed to execute them.
	Continuous improvement strategy	• Identify Industry 4.0 projects able to solve business and operational issues. • Identify IT infrastructure and networking projects needed to support Industry 4.0 projects and the Industry 4.0 strategy.

The actions for the preparation phase in Table 2 are used to prioritize the list of projects based on the manufacturing SME's strategic objectives and capacity and to ensure a management structure involving the right stakeholders, the tools and processes to manage the project portfolio and organizational changes are implemented. Actions to support the management and execution of each project are also present, as well as actions to ensure that the manufacturing SME puts together a project team able to deliver the projects. Finally, actions to ensure the SME's hierarchical line alignment are implemented, as well as to ensure that the project roadmap, management tools, processes, and governance are communicated.

Table 2. Actions to support CSF in the preparation phase.

Preparation Phase	Critical Success Factors	Actions
Industry 4.0 project prioritization	Align Industry 4.0 strategy to business strategy	• Compare the Industry 4.0 projects' objectives with the priority of the strategic objectives. • Compare the Industry 4.0 projects' funding with the funding and granting strategy. • Evaluate the Industry 4.0 projects' technology pre-requisites. • Create an impact vs. effort matrix to classify the projects based on impact and the SME's capabilities to deliver them. • Position the Industry 4.0 projects within an Industry 4.0 roadmap.
	Alignment along hierarchical line	• Ensure that the steering committee is involved in the prioritization process. • Validate the Industry 4.0 projects' roadmaps with the SME high management team.
	Communication management	• Communicate the Industry 4.0 projects' roadmaps at every level of the company.
Implementing an Industry 4.0 transformation management structure	Alignment along hierarchical line	• Create and implement an Industry 4.0 transformation governance. • Ensure that the steering committee is involved with the Industry 4.0 transformation governance.
	Communication management	• Create and implement a communication plan to update the SME's management and employees.
	Continuous improvement strategy	• Implement tools and processes to manage support and improvement functions once 4.0 projects are completed. • Implement tools and processes to identify and gather new Industry 4.0 project propositions.
	Organizational culture and change management	• Create and implement a change management plan. • Ensure that the change management plan involves change management as part of the Industry 4.0 projects. • Ensure that the change management plan involves change management needed to manage and support the Industry 4.0 transformation.

Table 2. *Cont.*

Preparation Phase	Critical Success Factors	Actions
Implementing an Industry 4.0 project delivery approach	Project management	• Implement project management tools and processes to plan, monitor, and manage the Industry 4.0 project. • For each Industry 4.0 project, identify the stakeholders. • Implement tools and processes to mitigate the risk of Industry 4.0 projects.
	Teamwork and team composition	• Create and assign an Industry 4.0 project manager role. • Identify and allocate internal resources for Industry 4.0 projects. • Ensure that the team members are familiar with the principles and technologies of Industry 4.0. • Identify and hire missing external resources needed to execute the Industry 4.0 projects.
	Communication management	• Create a communication and training plan for each Industry 4.0 project. • Implement tools and processes to facilitate communication, coordination, and collaboration between the team members.
	Employees' training and knowledge management	• Establish and document the stakeholders' and team members' roles and responsibilities.

Table 3. Actions to support CSF in the Execution phase.

Execution Phase	Critical Success Factors	Actions
Industry 4.0 project execution and management	Project management	• Control and adjust the project's budget and schedule during the project execution.
	Teamwork and team composition	• Ensure the coordination and collaboration between the team members, external resources, and stakeholders of the projects.
	Communication management	• Perform regular follow-up on the progress of Industry 4.0 projects at different levels of governance.
	Employees' training and knowledge management	• Document change to the IT infrastructure and architecture of the company. • Document the new processes and technologies implemented. • Create, implement, and document a support process for each new technology. • Train employees on how to use the new technologies and processes.
Industry 4.0 project post-mortem	Project management	• Perform a project post-mortem after each Industry 4.0 project. • Identify the critical success factors of each Industry 4.0 project. • Evaluate the gap between the estimated and actual budget and schedule. • Identify elements from the transformation management structure and project delivery approach that negatively impacted the project.
	Alignment along hierarchical line	• Involve the stakeholders of the project in the post-mortem. • Obtain feedback from the employees and managers of the departments where the technology was implemented.
	Teamwork and team composition	• Evaluate the presence or absence of internal expertise needed for the project. • Evaluate the performance of the project teams as per their roles and responsibilities. • Evaluate the relationship with external partners and suppliers on the projects.

Table 3. *Cont.*

Execution Phase	Critical Success Factors	Actions
Industry 4.0 management and project delivery approach revision	Align Industry 4.0 strategy to business strategy	• Evaluate the propositions for new Industry 4.0 projects. • Revise the project portfolio and roadmap.
	Alignment along hierarchical line	• Revise the governance of the Industry 4.0 transformation. • Validate the revision and the change with the proper stakeholders and steering committee.
	Communication management	• Revise the communication plan for the Industry 4.0 transformation. • Communicate the revision to the project team, steering committee, and stakeholders
	Project management	• Revise the project management tools and processes to better plan, monitor, and execute the projects. • Train the project teams on the revised tools and processes.
	Teamwork and team composition	• Revise the role and responsibilities of the project teams.
	Organizational culture and change management	• Identify organizational change to better support the management of the Industry 4.0 transformation of the company.

For the execution phase seen in Table 3, nearly all the CSFs are involved except *Conducting a study prior to Industry 4.0 projects*. Indeed, actions to ensure excellent communication and collaboration between the project teams, external contractors, and the stakeholders of the Industry 4.0 projects are present in the Project execution and management steps. Actions to properly train the employees and manage the knowledge developed during the Industry 4.0 projects are also present. Meanwhile, actions to review the performance of the implemented processes and tools to support and manage the Industry 4.0 projects are presented in the Industry 4.0 project post-mortem step. Finally, actions to revise and implement changes to the processes, tools, project portfolio, and roadmap are presented in the Industry 4.0 management and project delivery approach revision step.

While past research on CSFs only identified a list of actions to support each CSF [58,70,71], within each step and phase, the proposed methodology identifies and positions the actions needed to support the CSFs of Industry 4.0 transformation in manufacturing SMEs. It allows an SME to clearly identify the actions it needs at its current Industry 4.0 transformation step and plan the following actions accordingly. It also allows the SME to identify the CSFs it must implement at its current step, allowing it to gradually and iteratively implement all the CSFs needed to successfully manage its Industry 4.0 transformation.

When comparing these actions to past studies, similarities can be found. For each CSF, actions from other models that can be applied to the context of manufacturing SMEs could be found. For example, all past models indicate the necessity of allocating resources to the project teams and ensuring that tools and processes are implemented to manage the project scope, schedule, and budget. The same actions can be found in our study and are aligned with best project management practices. Similar actions can also be found within the *Align the Industry 4.0 strategy with the business strategy* CSF, with actions to align the ERP and supply chain system implementation with the business strategy. The *Communication management* CSF is also supported by similar actions between our study and other studies on CSFs.

However, some differences, influenced by the context of the Industry 4.0 transformation process of manufacturing SMEs, can be found, mainly within the *Leadership* and *alignment along hierarchical line* CSF. While past studies indicated that the champion must be part of the company's top management [58,71], our results indicate that, in the context of manufacturing SMEs, the champion should not be a top executive within the company but rather a manager supervised by the top executives. Our results also indicated the importance of creating a steering committee to supervise the Industry 4.0 transformation, while past studies did not. Finally, since the past studies aimed at identifying actions within a single project, none considered actions aimed at reviewing the project portfolio,

management structure, and project delivery approach in an iterative manner. Our study also includes actions to support the *Continuous improvement strategy* CSF, which is not part of past models since they were not developed to be used in the context of iterative projects.

When looking at these actions, many of them were not specific to the context of manufacturing SMEs and could be applied to larger organizations that decide to perform their digital transformation through a set of iterative projects. Critical success factors like *Align industry 4.0 strategy to business strategy* or *Leadership* are not specific to manufacturing SMEs and are valid for larger organizations. Thus, the actions to implement and support them will be similar between large and small companies. However, the steps and phases within which the actions take place can differ between large and small organizations, especially if the large company does not follow an iterative approach to its digital transformation.

Moreover, these actions were primely identified in response to the challenges of manufacturing SMEs, their context, and the critical factors identified to support their digital transformations. We also validated these actions with a panel of experts with specific experience in manufacturing SMEs and the managers of manufacturing SMEs. The actions have not been validated by experts specialized in the digital transformation of large organizations.

The limitation of the presented methodology resides within the actions themselves. The actions presented in this research are exclusively associated with the CSFs identified earlier. As such, this research did not introduce actions linked to the creation and management of deliverables within each step of the Industry 4.0 transformation process. This research also does not present the sequence and dependencies of these actions within and between each step. Since the objective of this paper is to propose a methodology to manage the digital transformation of manufacturing SMEs by the operationalization of well-established CSFs, we did not test the performance of this methodology within a manufacturing SME. Future research could present a complete and generic model to manage the Industry 4.0 transformation of manufacturing SMEs by adding, sequencing, and linking these actions with different deliverables and actions meant to execute and manage Industry 4.0 projects. Future research could also evaluate the difference between this methodology and other methodologies specialized in large organizations. Finally, future research could also validate and enhance this methodology by testing it within manufacturing SMEs.

7. Conclusions

This paper proposed a methodology to manage the Industry 4.0 transformation process of manufacturing SMEs through the operationalization of CSFs. A literature review was performed to determine the list of actions and position them within the steps and phases of an Industry 4.0 transformation process. These actions were then submitted to a panel of Industry 4.0 experts using a Delphi–Régnier methodology. Based on the opinions of these experts, a methodology was developed and proposed.

This study's main theoretical contribution is the following: By proposing a list of actions complementing the information already available in the literature with a study performed with both practicians and academics, the study of CSFs in Industry 4.0 was enriched. In addition, by positioning these actions into the different steps, we can identify the timely impact of CSFs in the overall Industry 4.0 transformation process.

This study also has practical implications. The identified actions can serve managers and consultants in digital transformation projects by helping them better plan and execute their Industry 4.0 transformation plans. Indeed, the methodology provides a list of specific actions facilitating the occurrence of the CSFs needed for transformation.

This study possesses limitations worth mentioning. Since it was performed using a panel of experts, this study involves a subjective bias related to the choice of experts from the researchers' academic and professional networks. It was difficult for the research to be completely free from this potential bias despite the research team's desire for neutrality and the attention paid to the complementarity and coherence of the profiles when selecting the experts. Furthermore, a small number of professionals validated the list of actions. We

could have obtained more accurate results and complementary information by performing the study with a higher number of experts.

Another limitation is that our research is mainly qualitative. Since we aimed to propose a methodology to manage the Industry 4.0 transformation of manufacturing SMEs, the scope of our study and its prospective aspect did not allow us to envision a more quantitative approach. On the other hand, our research methodology allowed us to collect empirical data from expert opinions to identify the main actions to support the critical success factors needed to manage the Industry 4.0 transformation of manufacturing SMEs.

Future research could involve studying the presence of said actions within multiple manufacturing SMEs and analyzing the impact of the presence or absence of said actions on the performance, challenge, and risks linked to their Industry 4.0 transformation plans. Since most actions highly depend on the specific context of the manufacturing SME, future research could identify which specific elements of an SME context should be considered and how specific actions should be performed in each case. Finally, since the model was not empirically validated in a manufacturing SME, future researchers could test the methodology and enhance it with their results to assess its effectiveness and generalize it.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors due to privacy.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. First Questionnaire Statements and Vote Distribution

1. *When establishing a digital transformation strategy, the manufacturing SME must:*

1.1. Revise the business strategy and business model to take into account digital technologies

1.2. Review the strategic financial and operational objectives to ensure the alignment of its 4.0 strategy with its business strategy.

1.3. Identify the strategic and financial objectives that will be supported by the digital transformation strategy

1.4. Appoint a digital transformation champion.

1.5. Ensure that the champion belongs to high management

1.6. Validate the digital transformation strategy with all the departments and business units

1.7. Obtain a commitment from the directors and managers of all the departments

1.8. Communicate the strategic vision of digital transformation to all the employees and managers

1.9. Define an IT architecture vision to support its digital transformation.

2. *When assessing the current situation, the manufacturing SME must:*

2.1. Perform a diagnostic on the performance of all its business processes and technologies

2.2. Analyze its infrastructure and its current IT and business architecture

2.3. Involve the company's managers and employees in this step.

2.4. Assess the company's ability to undertake 4.0 transformation projects

3. *When identifying Industry 4.0 projects, the manufacturing SME must:*

3.1. Align 4.0 projects with the company's strategic 4.0 objectives and business strategy.

3.2. Identify for each of the 4.0 projects the potential IT infrastructure changes to be implemented to support them.

3.3. Identify IT infrastructure and architecture projects to support its 4.0 vision and strategy.

3.4. Conduct a needs analysis of resources and expertise for each 4.0 project.

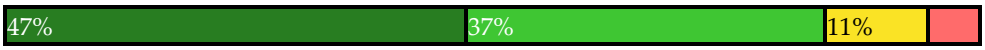
3.5. Define the objectives of each project, their technological prerequisites, their schedule and budget, as well as the potential risks.

3.6. Identify 4.0 projects to address operational issues to support its continuous improvement strategy.

4. *When prioritizing Industry 4.0 projects, the manufacturing SME must:*

4.1. Prioritize its 4.0 projects by taking into account the priority of its strategic objectives.

4.2. Prioritize and sequence its 4.0 projects according to their technological requirements.es.



4.3. Prioritize and sequence 4.0 projects based on the company's ability to successfully execute its projects.

4.4. Prioritize and sequence IT infrastructure projects that will support 4.0 projects.

4.5. Validate the sequence and prioritization of 4.0 projects with the champion and senior management of the company.

4.6. Communicate the prioritization and sequencing of 4.0 projects to the company's managers and employees.

4.7. Train employees on general Industry 4.0 concepts to facilitate change management.

5. *When setting up an Industry 4.0 transformation management structure, the manufacturing SME must:*

5.1. Determine the level of authority the champion will have to manage the 4.0 transformation.

5.2. Set up a governance system to monitor projects and escalate issues to the company's management.

5.3. Implement a communication plan to employees and managers on the progress of the company's 4.0 transformation.

5.4. Implement a proactive change management plan and reactive change processes to facilitate change management during 4.0 transformation.

5.5. Allocate resources for solution 4.0 exploration and project review prior to implementation.

5.6. Align the structure and processes of Transformation 4.0 with the company's existing internal structures and processes.

6. *When implementing an Industry 4.0 project delivery approach, the manufacturing SME must:*

6.1. Designate a project manager reporting to the champion to manage 4.0 projects.

6.2. Identify the stakeholders of 4.0 projects and set up a communication plan with them.

6.3. Include a prototyping or proof-of-concept phase at the beginning of projects to test 4.0 solutions before deployment.

6.4. Create a validation process for 4.0 solutions before their deployment in the enterprise.

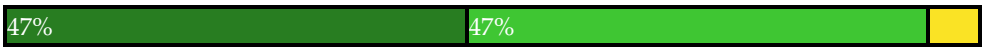
6.5. Designate and set up a team capable of carrying out 4.0 projects.

6.6. Hire or subcontract the missing resources identified for the various 4.0 projects.

6.7. Formally document the roles, authorities, responsibilities, and skills of all team members.

6.8. Include an employee training phase for each 4.0 project and for each 4.0 solution deployed.

6.9. Include a change management plan within each 4.0 project plan.



6.10. Implement project management tools and processes for planning, monitoring and controlling 4.0 projects.

6.11. Implement tools and processes to manage the risks identified for each project.

6.12. Implement tools and processes to enable coordination and collaboration between project team members.

7. *When executing Industry 4.0 projects, the manufacturing SME must:*

7.1. Conduct regular follow-ups on the progress of 4.0 projects with the project manager and the Champion.

7.2. Validate selected 4.0 technologies with 4.0 project stakeholders.

7.3. Document and communicate changes to the company's IT infrastructure and architecture.

7.4. Ensure coordination and collaboration between project team members.

7.5. Create documentation and processes to support 4.0 technologies in deployment.

7.6. Train employees on new technologies and processes resulting from 4.0 projects.

7.7. Adjust the on-boarding process and documentation for new employees to reflect the changes implemented during the project.

7.8. Control the budget and schedule of 4.0 projects.

7.9. Involve employees in the validation and implementation of 4.0 technologies.

8. *During the post-mortem of Industry 4.0 projects, the manufacturing SME must:*

8.1. Involve stakeholders in 4.0 projects during project feedback.

8.2. Obtain feedback on the project from employees and managers of the departments where the technologies were implemented.

8.3. Identify elements of the management structure and delivery approach that negatively impacted the delivery of Project 4.0.

9. *When reviewing the Industry 4.0 transformation structure, approach, and portfolio, the manufacturing SME must:*

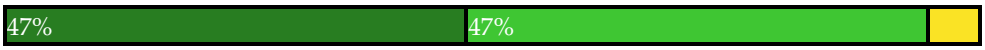
9.1. Revise the project portfolio according to the gains obtained from the projects carried out on the strategic objectives.

9.2. Revise the communication plan according to the changes that can be made to the stakeholders.

9.3. Review transformation governance based on changes to the project escalation and tracking process.

9.4. Review project management tools and processes to improve project planning, monitoring, and execution.

9.5. Identify the organizational changes required to support the implementation of 4.0 projects.



9.6. Encourage employees to suggest ways to improve 4.0 projects and their management.

10. *When implementing revisions, the manufacturing SME must:*

10.1. Validate revisions to the structure and delivery approaches of 4.0 projects with stakeholders.

10.2. Validate changes to the project portfolio by the company's senior management.

10.3. Validate the alignment of the revised project portfolio with the company's strategic objectives.

10.4. Train employees and managers on the revised elements.

10.5. Document revisions and organizational changes made.

Appendix B. Second Questionnaire Statements and Vote Distribution

1. *Characteristics of the Industry 4.0 champion*

1.1. The Industry 4.0 transformation champion plays an informal role within the manufacturing SME

1.2. The Industry 4.0 transformation champion has a formal position within the manufacturing SME

1.3. The Industry 4.0 transformation champion within a manufacturing SME must be the company's CEO

1.4. The Industry 4.0 transformation champion within the manufacturing SME should be a member of the company's senior management, but not the CEO.

1.5. The Industry 4.0 transformation champion within the manufacturing SME should be a manager who reports to a member of the company's senior management or CEO.

1.6. The Industry 4.0 transformation champion is directly responsible for ensuring the success of the manufacturing SME's Transformation 4.0.

1.7. The Industry 4.0 transformation champion plays a communicator role responsible for educating the business on digital transformation as well as communicating the progress of Industry 4.0 projects.

1.8. The Industry 4.0 transformation champion is responsible for identifying Transformation 4.0 projects in the manufacturing SME.

1.9. The Industry 4.0 transformation champion is responsible for prioritizing Transformation 4.0 projects in the manufacturing SME.

1.10. The Industry 4.0 transformation champion is responsible for establishing a governance structure to track Industry 4.0 projects.

1.11. The Industry 4.0 transformation champion must assume the role of 4.0 project manager.

1.12. If they are not the same person, the 4.0 Project Manager must report hierarchically to the Industry 4.0 transformation champion.

1.13. The Industry 4.0 transformation champion must have prior experience in digital transformation.

2. *Manufacturing SME's capacity to realize its Industry 4.0 projects*

2.1. When a manufacturing SME evaluates its capacity to carry out Industry 4.0 projects, it must assess its financial means and determine a budget to be allocated

2.2. When a manufacturing SME assesses its ability to carry out Industry 4.0 projects, it must assess the availability and skills of the company's internal resources who will be responsible for implementing these projects

2.3. When a manufacturing SME assesses its ability to deliver Industry 4.0 projects, it should evaluate how its internal processes and practices can facilitate or hinder its Industry 4.0 projects

2.4. When a manufacturing SME evaluates its capacity to carry out Industry 4.0 projects, it must assess the level of openness and reluctance of its managers and employees towards the projects considered.

2.5. A manufacturing SME must consider all the potential external help available (grants, consultants, integrators, trainers, etc.) when evaluating its ability to undertake its Industry 4.0 transformation.

2.6. When a manufacturing SME assesses that its capacity to undertake Industry 4.0 projects is insufficient, it must identify projects (financing, hiring, organizational change) that will allow it to obtain the necessary capacity to carry out its Industry 4.0 projects.

Appendix C. Items Matrix of the First Questionnaire (First Round)

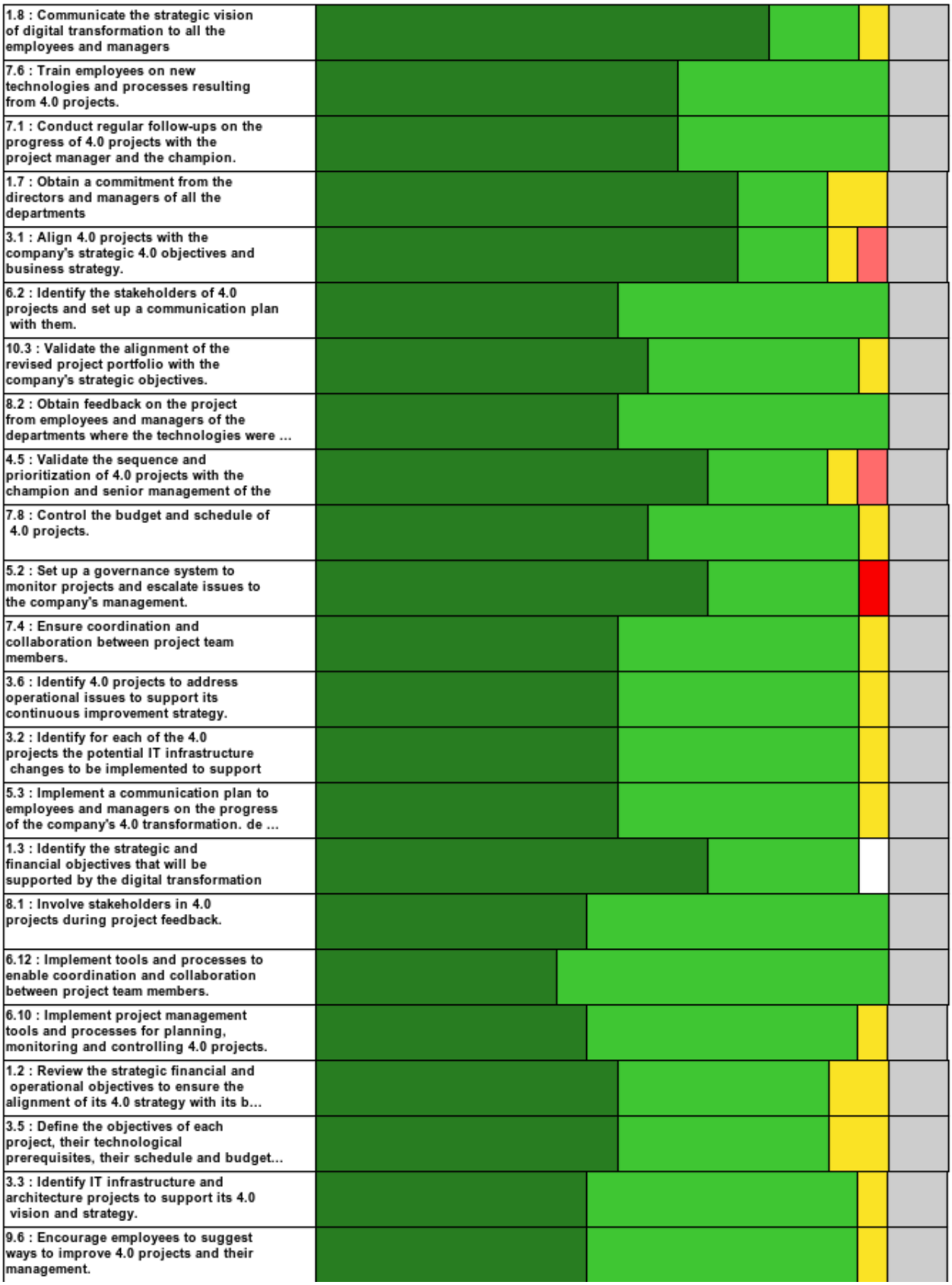


Figure A1. Item Matrix of First Questionnaire—1 of 3.

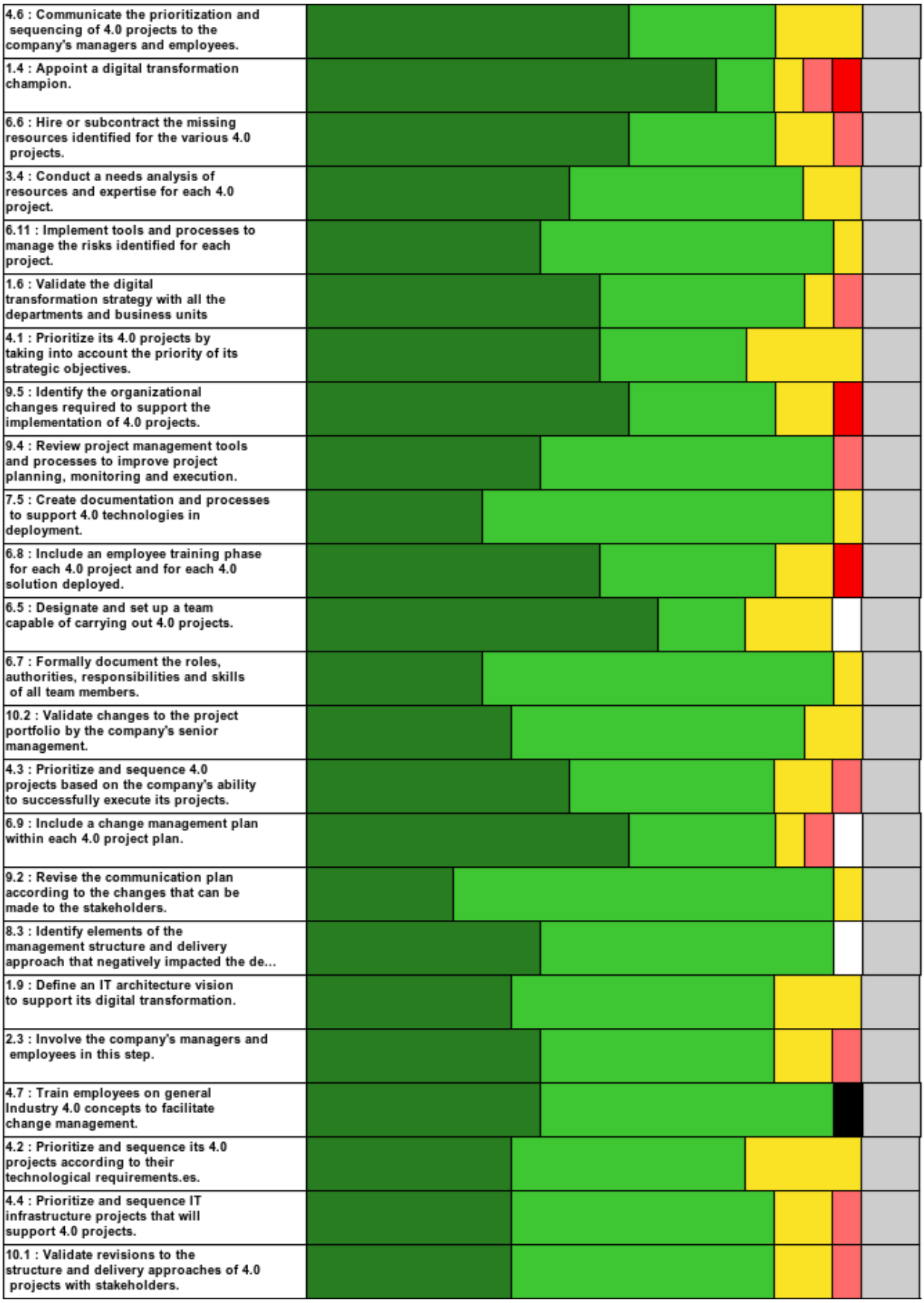


Figure A2. Item Matrix of First Questionnaire—2 of 3.

Figure A3. Item Matrix of First Questionnaire—3 of 3.

Appendix D. Items Matrix of the Second Questionnaire (Second Round)

Figure A4. Item Matrix of Second Questionnaire.

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