Implementing Industry 4.0 Principles and Tools in SME

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Contributor: Samir Abdulnour , Chantal Baril , Georges Abdulnour , Sébastien Gamache

Small and medium enterprises (SME) face various challenges in order to remain competitive in a global market. Industry 4.0 (I4.0) is increasingly presented as the new paradigm for improving productivity, ensuring economic growth, and guaranteeing the sustainability of manufacturing companies. I4.0 refers to the integration of information technologies (internet of things, cyber–physical systems, cloud computing, AI, etc.) and automation (robots, cobots, automated guided vehicles, etc.) in every sphere of a company, vertically and horizontally, to improve performance. However, SMEs are ill equipped and lack resources to undertake this digital shift.

I4.0 intelligent manufacturing modular design modular product dynamic cellular manufacturing

flexibility agility

1. Introduction

Small and medium enterprises (SMEs) face various challenges in setting themselves apart and remaining competitive in a global market. Raymond Chabot Grant Thornton [1] conducted a survey with 300 managers of companies with 10 to 499 employees to identify the challenges facing SME. The results show that the key challenges are labor recruiting and retention (60%), competitiveness (35%), digital shift (18%), and access to financing (12%). The labor shortage already plaguing the Quebec manufacturing sector for years worsened with the COVID-19 pandemic. Today, it is a constraint on recovery and economic growth in several manufacturing companies. In addition to juggling labor problems, SMEs must stand out in an increasingly competitive and globalized market. To increase their competitiveness, SMEs rely on greater productivity and often use the Lean [2] and Six sigma [3] improvement programs to succeed. SMEs must also meet growing demand for increasingly personalized products. They must move from mass production to personalized mass production. This situation requires SMEs to review their methods and production systems to make them more productive, flexible, and, above all, agile [4].

Today, the fourth industrial revolution, known as Industry 4.0 (I4.0), is increasingly presented as the new paradigm for improving productivity, ensuring economic growth, and guaranteeing the sustainability of manufacturing companies. I4.0 refers to the integration of information technologies (internet of things, cyber–physical systems, cloud computing, AI, etc.) and automation (robots, cobots, automated guided vehicles, etc.) in every sphere of a company, vertically and horizontally, to improve performance [5].

Several topics concerning the implementation of I4.0 have already been analyzed in the literature. These include studies on success factors [6][7], risks [7], opportunities [7], barriers [8][9], challenges [6][10], technological tools and their integration [6][11][12][13], design principles [6][11][12], 4.0 maturity or readiness assessment [6][11][12][14][15][16], and implementation strategy development [11][12][17][18]. The implementation of I4.0 concepts by small and medium-sized enterprises (SMEs), where the ideal balance between Industry 4.0 implementation costs and real benefits is unknown, is of paramount concern [19]. Indeed, SMEs are ill equipped and lack resources to undertake this digital shift [4]. According to Horvath and Szabo [20], multinational enterprises have higher driving forces and lower barriers to Industry 4.0 than SMEs. According to Cotrino et al. [17], the implementation of Industry 4.0 technologies in SMEs is poorly documented from a practical point of view, and the existing implementation strategies for Industry 4.0 do not focus on SMEs.

2. Industry 4.0

Industry 4.0 (I4.0) is a concept rooted in a reflection initiated by the German government on the future of the manufacturing sector. The objective is to position the manufacturing sector to be as productive and flexible as possible. Software, equipment, and data connectivity, as well as processing big data and cybersecurity, are key factors in implementing I4.0. These factors make it possible to create intelligence in the manufacturing system that then becomes capable of greater adaptability in production and of more efficiently allocating resources [21].

I4.0 is based on several design, tool, and technological trend principles that guide enterprises in their digital shift [22]. De Paula Ferreira et al. [23] identified 17 design principles that describe the tenets of I4.0 and help companies to implement the concept. **Table 1** presents these principles.

Table 1. Design principles of Industry 4.0.

Design Principles of Industry 4.0			
1	Vertical integration	10	Autonomy
2	Horizontal integration	11	Optimization
3	End-to-end engineering integration	12	Flexibility
4	Smart factory	13	Agility
5	Interoperability	14	Service orientation
6	Modularity	15	Smart product
7	Real-time capability	16	Product personalization
8	Virtualization	17	Corporate and social responsibility
9	Decentralization		

All of the I4.0 design principles are linked to a certain extent. Although the goal of this study is not to analyze all of the relationships and/or dependencies of these principles, it is important to highlight the key relations described in the articles analyzed. These relationships are [23]:

- Interoperability enables vertical and horizontal integration [24][25];
- Modularity enables flexibility, agility, and product personalization [22][26][27];
- Vertical integration enables smart factories [28][29];
- Smart manufacturing enables digital end-to-end engineering [30];
- Virtualization of production systems depends on real-time capabilities [22][27];
- Decentralization can be achieved through smart products [27][30][31].

Evidently, implementing I4.0 design principles obliges SMEs to use different technological tools. Bosman et al. [32] investigated the role of firm size, access to funds, and industry type on the decision to invest in and deploy various Industry 4.0 technologies. The findings suggest that manufacturers with fewer than 20 employees and/or less access to funds (sales of less than USD 10 million) prioritize digital factory floor technologies (e.g., technology directly impacting productivity, quality, and safety of manufacturing processes). Larger manufacturers with 20 or more employees and/or access to more funds (sales greater than or equal to USD 10 million) prioritize enterprise support operations technologies. Moeuf et al. [7] selected 12 experts to conduct a Delphi study supplemented by Régnier’s abacus. The experts noted that, a priori, all of the technological tools were accessible to SMEs, and they said that it is not necessary to exploit all of the technologies to implement Industry 4.0.

As presented in **Figure 1**, Gamache et al. [11] identified 24 technological tools related to I4.0 that they grouped into five categories. The technological tools are the methods that SMEs can use to implement the I4.0 concepts and design principles.

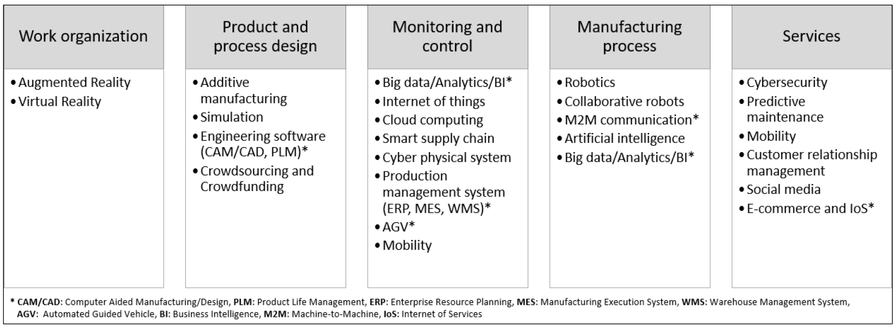

Figure 1. The 24 I4.0 technological tools.

3. Implementation Strategies for I4.0 Principles and Tools

Obviously, SMEs that wish to undertake a digital shift cannot implement all of these principles and tools at once. Companies must make choices. There are some interesting studies in the literature concerning I4.0 implementation strategies.

Based on a systematic literature review, Wankhede and Vinodh [6] established a conceptual framework to guide automotive industry practitioners towards I4.0 implementation. However, the framework needs to be validated with industries to ensure its practical validity.

Cotrino et al. [17] proposed a six-step roadmap to facilitate decision making and access to Industry 4.0 technologies in the production areas of SMEs. Their results show that implementing Industry 4.0 solutions according to this roadmap helps SMEs to select appropriate technologies. In addition, three examples are presented to optimize production and enhance the productivity and efficiency of a smart assembly line (SAL). The results demonstrate that SMEs can access several Industry 4.0 technologies with low-cost investments.

Amaral and Peças [16] proposed a framework for assessing companies with low maturity levels, such as most existing SMEs. The proposed holistic model considers all Industry 4.0 dimensions (six dimensions and 26 sub-dimensions) and is detailed enough in its initial levels to properly assess SMEs. Each sub-dimension is assessed on a scale of 0 to 5 based on its level of maturity. They suggested developing a roadmap for the introduction of I4.0 in companies.

Wamkhede and Vinodh [15] developed a conceptual model consisting of six criteria—Technology, Organization and Management, Process, Legislation, Product, and Employee—and 50 factors related to I4.0 readiness for the automotive component manufacturing industries. The Readiness Index was computed based on the fuzzy logic approach. The ranking score makes it easier for organization management to identify significantly weak readiness factors. The study's findings revealed that the organization in the case study needed to develop strategies to improve its I4.0 readiness.

Liebrecht et al. [18] proposed a case-specific analysis and evaluation of available I4.0 methods to select those most suitable for an individual company. In the first phase of their methodology, a set of relevant methods was derived according to the company's type of production (manual or automated, several small-volume products or a few high-volume products). There were also methods for universal application. This method served as a basis for the next phases of their methodology. The objective of phase 2 was to derive a subset of value-added introduction scenarios for the method selected in phase 1. All methods had to be assessed strategically and to be valued from an economic perspective. The methods were assessed based on the company's specific characteristics, its strategic focus, and its (market) environment. In phase 3, by varying decision parameters, several beneficial scenarios were derived, and they contained a prioritized implementation sequence of all methods. These scenarios were put into a System Dynamics model to consider the influence of dynamic and time-dependent parameters. Based on the corporate strategy, a recommended Industry 4.0 roadmap was identified, showing financial and strategic potential, as well as implementation order and duration. Although this research is very interesting, it has several limitations, including that the toolbox is not linked with existing integrated production system toolboxes and lean management. This is necessary to support, in particular, small-sized companies in implementing integrated production systems, which combine lean management and Industry 4.0.

Gamache et al. [11] and Gamache [33] proposed an assessment model in the form of a questionnaire to assess the impact of 24 business practices on the digital performance of companies. The business practices represent the methods implemented by companies to improve their performance. Digital performance is defined as the assessment of the progress of a company's digital shift according to I4.0-related business practices. Each business practice is assessed on a scale of 0 to 4 with regard to its level of digital maturity, where 0 = Nonexistent, 1 = Rudimentary, 2 = Disciplined, 3 = Integrated, and 4 = Foreseeable. Some twenty companies were assessed using this questionnaire to determine their digital performance. The business practices assessed were classified into four categories according to their impacts on the digital performance of companies (**Table 2**).

Table 2. Categories for classifying business practices.

Business Practices	Impact on the Digital Performance of Companies
Essential	Significant impact and potential improvement > 20%
Priority	Significant impact and potential improvement < 20%
Not priority	Insignificant impact and possible improvement > 10%
Specific cases	Insignificant impact and possible improvement < 10%

Table 3 shows the 24 business practices grouped into these categories [33].

Table 3. Classification of business practices according to Gamache [33].

Category	Business Practices	
Essential	1	Develop a digital vision and strategy
	2	Develop and clarify the digital ecosystem and architecture (with IT bridges for example)
	3	Demonstrate commitment and set an example
	4	Be proficient in digital tools
	5	Automate processes: implement ERP, MES, IoT, Robots, Cobots, AI systems
	6	Ensure data quality
	7	Benefit from e-commerce advantages (product configurator or a transactional website)
Priority	8	Improve change management
	9	Encourage Agility and Innovation
	10	Implement Lean and Continuous Improvement: define relevant performance indicators (KPI)
	11	Ensure cybersecurity
	12	Optimize data delivery (ERP, MES, and dynamic dashboard systems)
	13	Implement Mass Personalization
	14	Maximize the operational use of data (IoT, MES, dynamic dashboards)
	15	Maximize the strategic use of data
Non-priority	16	Develop new business models
	17	Deploy resources and investments
	18	Optimize skill acquisition and development (video training programs)
	19	Maximize internal communication (collaboration platform)

Category		Business Practices
	20	Improve the data collection system (RFID, IoT, sensors, cloud computing)
	21	Ensure customer loyalty, service, and loyalty
Specific cases	22	Technology monitoring
	23	Openness to the outside
	24	Co-creation

se results (**Table 4**).

Table 4. Digital shift strategy proposed by Gamache [33].

Preliminary Step	• Map the value chain to ensure process control • Develop a strategic company vision and plan
Audit Step	• Assess the company's digital performance
Planning Step	• Identify the business practices to implement (digital or not) • Prioritize and plan projects in a digital plan
Implementation Step	• First, implement digital and non-digital business practices in the priority category • Implement Lean and optimize before deployment
Deployment Step	• Deploy digital and non-digital solutions in all business processes
Optimization Step	• Correct, optimize, and implement the next project on the list

Unlike Liebrecht et al. [18], Gamache [33] recommended implementing Lean and optimizing before deployment at the Implementation Step (**Table 4**). When analyzing the priority business practices in the Implementation Step, note that they are related to the personalization and agility design principles presented previously in **Table 1**. Here are the details of the link between these principles.

Modularity makes it possible to personalize the product by combining, modifying, or adding modules to a standard product structure [12][22][26][34]. The principle of modularity is based on the concept of standardization. By reducing makespan, modularity makes production systems more flexible and agile in order to respond to variable demand [33]. Modular and reconfigurable manufacturing systems [35] make it possible to quickly combine (plug and play) modules with compatible software interfaces and materials [27][36], and to which functionalities can be added or removed more quickly [25][26][37]. Modularity can be implemented in manufacturing system design as a dynamic production cell [38] and in the product design at the conceptual design stage [39].

The principle of personalizing a product requires the production system to be adapted to produce relatively small batches of goods personalized to the customer's tastes.

A flexible production system is essential to make profitable the small-lot production imposed by mass personalization [40]. Flexibility refers to a production system capable of manufacturing small batches of a wide variety of products immediately and without implementation costs. Modular product design serves to make manufacturing systems more flexible and, consequently, offer a variety of products at a lower cost and in a timely manner [41]. The methods for improving manufacturing system flexibility include automation (robots), organizing into dynamic cells, balancing production lines, etc.

Agility is a company's capacity to react quickly to various changes that cannot be foreseen. Agility allows companies to increase their resiliency capacity and to remain competitive when there are, for example, major market variations [42]. To be agile, manufacturing systems must be adaptable or reconfigurable. A system is reconfigurable when the structure of the system within a family of products can be changed quickly to adjust production capacities and functionalities to respond to changing market requirements [43][44]. This requires reactive and flexible manufacturing operations to produce individualized products in dynamic batch sizes, on a wide scale, and in a profitable manner [45][46]. Methods for improving a manufacturing system's agility include automation (cobots), organizing into dynamic cells, employees with multiple skills, etc. Sharp et al. [47] compared mass, flexible, and agile production systems.

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