STANDARDS RESEARCH

Unlocking the Potential for Smart Manufacturing in Canada

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Executive Summary

Smart manufacturing (SM) refers to the major progression toward more sophisticated and technologically advanced processes related to manufacturing. Globally, jurisdictions such as the United States, Germany, and Singapore are viewed as leaders in today's global SM ecosystem. These countries consistently invest in innovation, sustainability, and workforce development, propelling the evolution of manufacturing practices worldwide. For decades, Canada has been recognized for its strong manufacturing economy, driven by large and complex domestic automotive, food processing, pharmaceutical, and aerospace and defence industries. However, despite strong manufacturing foundations, Canada's SM sector is not as mature as the SM sectors in the international jurisdictions mentioned above.

This project reviewed and assessed the Canadian SM landscape with emphasis on barriers and challenges, including those that could be potentially addressed through standards. It explored the current state of SM in Canada, government policy, funding, and regulations, relevant standards in SM, and Canada's SM adoption challenges.

The research presents six major identified challenges to strengthening Canadian SM and proposes recommendations, including standards-based solutions, to help address these challenges. The identified challenges are as follows:

- an unclear value proposition to Canadian companies with respect to return on investment and lack of clarity in the specific outcomes of adopting SM technologies;
- difficulties associated with capital access for small and medium-sized companies to invest in and operate SM solutions;
- a prominent and growing national talent gap associated with the highly skilled workers necessary to implement and operate SM technologies;
- complex technical challenges related to interoperability and cyber security as a result of the implementation and interconnection of SM solutions;
- national under-investment in the intellectual property assets necessary to scale, commercialize, and realize the financial gains of SM investments; and
- lack of a clear national SM strategy that could organize and synergize what several interviewees see as a fragmented manufacturing ecosystem overall.

The report presents a list of proposed recommendations to help tackle those challenges and better support SM adoption in Canada, including through the use of standards.

Achieving successful SM implementation in Canada requires a thoughtful approach that balances short-term requirements with long-term vision. To navigate this journey effectively, organizations should grasp the essential components: infrastructure, skills, and processes. By simultaneously addressing technological advancements and human resource development, businesses could proactively prepare for seamless SM integration.

List of abbreviations

3D	three dimensional
5G	fifth generation
A&D	aerospace and defence
AI	artificial intelligence
AII	Accelerate Investment Incentive
AR	augmented reality
CAGR	compounded annual growth rate
CESMII	Clean Energy Smart Manufacturing Innovation Institute
CIC	Canada Innovation Corporation
CME	Canadian Manufacturers & Exporters
CPSMT	cyber-physically controlled smart machine tool
EIS	Enterprise Innovation Scheme
ESG	environmental, social, and governance
GDP	gross domestic product
GE	General Electric
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	intellectual property
ISED	Innovation, Science and Economic Development Canada
ISMS	information security management systems
ISO	International Organization for Standardization
LNI	Labs Network Industrie
MFCA	material flow cost accounting
ML	machine learning
NGen	Next Generation Manufacturing Canada
NGO	non-governmental organization
NIST	National Institute of Standards and Technology
NRC	National Research Council
R&D	research and development
RFID	radio-frequency identification
ROI	return on investment
SDO	standards development organization
SIF	Strategic Innovation Fund
SIRI	Smart Industry Readiness Index
SM	smart manufacturing
SME	small and medium-sized enterprise
SR&ED	Scientific Research and Experimental Development
SSC	Singapore Standards Council
TIAM	Toronto Institute of Advanced Manufacturing
TRL	technology readiness level
UI	user interface

"To remain competitive, the Canadian manufacturing sector will need to embrace and effectively implement smart manufacturing."

1 Introduction

Smart manufacturing (SM) is an evolution of the fourth industrial revolution, also known as Industry 4.0. This phase of digitization in the manufacturing sector is driven by disruptive trends such as data and connectivity, analytics, human–machine interaction, and advancements in robotics. Industry 4.0 and SM strive to revolutionize the way companies manufacture, improve, and distribute their products [1, 2]. SM uses advanced technologies like automation, data analytics, and artificial intelligence (AI) to enhance efficiency, effectiveness, and overall productivity. The term "smart manufacturing" generally refers to a modern-day approach to production that has implications for the full life cycle of a product from design to manufacturing and distribution. It also includes critical elements of the manufacturing ecosystem such as the supply chain and end-of-life management of products.

It is widely understood among manufacturing leaders, champions, industry observers, and researchers in Canada that, to remain competitive, the Canadian manufacturing sector will need to embrace and effectively implement SM [3]. To achieve success in this regard, there is an urgent need to examine and better understand the current global and national SM landscape, including the market forces and technology challenges and obstacles that are specifically affecting SM adoption, implementation, and growth in this country. A better understanding of how standardization and standard-based solutions can help Canadian manufacturing sector stakeholders address their SM-related challenges, as well as to better harness new and emerging SM digital transformation opportunities, is also critically important.

The global manufacturing landscape is undergoing significant transformation as technological advancements, including automation, digitalization, and AI, reshape industry and society. Indeed, the fourth industrial revolution sees numerous governments and industries around the world, including those in Canada, potentially reorienting their policies and resources toward SM.

The primary aim of this project is to assess the Canadian SM landscape, focusing on opportunities and barriers, and identify challenges that could be addressed through standardization. This report provides Canadian manufacturing stakeholders with an overview of successful SM implementations in advanced markets, the current state of SM in Canada, including adoption impediments, and federal/provincial initiatives supporting SM. It also examines emerging technological trends, the evolving regulatory landscape, and relevant SM-focused standards. Finally, the report offers recommendations on addressing impediments to SM in Canada.

The specific objectives include learning from SM successes in select international jurisdictions, understanding the state of SM in Canada and the challenges to its adoption, and reviewing relevant governmental and private initiatives, including funding and other support mechanisms. Additionally, the project aims to identify emerging technological trends affecting Canadian manufacturers, understand the evolving SM regulatory landscape, and explore relevant standards to inform Canadian efforts. Ultimately, the project seeks to provide a set of recommendations that could support the widespread adoption of SM in Canada.

2 Methods

The insights and recommendations presented in this report are derived from a methodology that includes a literature review, key informant small group interviews, and an integrated analysis of the findings.

- **Literature review** – Relevant documents related to SM approaches and standards, including academic papers, industry reports, company and government documents, and relevant websites, were reviewed. The document review was guided by themes such as: a) assessment of the current state of SM implementation in Canada; b) review of advanced global markets where SM has been successfully implemented; c) Canadian federal and provincial government initiatives supporting SM; d) current national and international standards relating to SM; e) challenges for Canadian manufacturers in implementing SM; and f) emerging technology trends related to SM implementation.

Several international jurisdictions with well-advanced SM and SM standards, specifically the United States, Germany, and Singapore, were selected for detailed analysis. These jurisdictions were chosen because of their relevance to the Canadian context and the availability of ample information on SM and SM standards. By examining the successes and challenges in these regions, the project aims to better illuminate the challenges and barriers facing SM in Canada and identify practical opportunities for potential improvement through standards.

- **Key informant interviews** – A total of 19 individuals as key informants participated in eight small group interviews. These participants were selected from a longer list of potential subjects assembled by the lead project consultants based on project needs. Interviews—approximately 60 minutes in length—were conducted electronically (e.g., Microsoft Teams). Interview notes were thoroughly reviewed to compile a list of potential themes and sub-themes (nodes and sub-nodes) for further analysis. Unique ideas raised by individual interviewees were also captured. This list was compared and contrasted with themes identified in the literature review. Similar or related themes were clustered together and labelled. These clusters were refined over time as patterns and associations were examined. The resulting nodes and their relationships were used to develop the possible solutions to challenges and recommendations contained in this report, aligning with the project's aims of identifying opportunities and barriers to SM implementation in Canada and addressing challenges through standardization.

Key informant interviews were an important source of information for this project. Leading Canadian industry actors, including policy-makers, representatives from manufacturing companies and industry associations, and researchers involved with SM and interested in SM-related standards, were asked in small groups to share their perspectives and first-hand knowledge and ideas on topics related to the project aims and objectives. A list of questions developed in advance (see Appendix A) was used to guide what can be described as 'flexible and focused conversations' about SM and SM standards.

During small group interviews, questions were not always asked in the same order, as facilitators would follow the general direction or pathway of the conversation as dictated by participants. Probes and prompts were also used to solicit more information or to clarity points made. Notes were taken by facilitators and observers. After each interview, the consultants discussed the emerging observations and insights.

These were then filed and used in the latter stages of the project to help illuminate project insights and themes, as well as possible solutions to challenges experienced by SM stakeholders, and to report conclusions and recommendations. Overall, interviews elicited valuable information, insights, and perspectives regarding the challenges facing the SM sector in Canada, including ideas about how standards could help to address them.

3 Results and Discussion

3.1 Smart Manufacturing Overview

3.1.1 Defining Smart Manufacturing

There are many definitions of SM in use today. There is no single "gold standard" definition used widely. Some definitions describe SM in terms of technologies that are considered "smart" and list specific ones. Others stay silent on specific technologies, and instead describe SM more broadly at a conceptual level. SM has been characterized as "data-driven optimization," "adaptive and agile production," "cyber-physical system integration," and "sustainable and environmentally conscious manufacturing." While many definitions often use similar words, there are important nuances that distinguish them from each other. Broadly speaking, some definitions tend to focus on SM as an approach or a system, while others emphasize the elements or ingredients of SM. Moreover, some involved with SM appear to use "SM" interchangeably with the somewhat older term "advanced manufacturing," while still others make distinctions between the two.

While it may not be necessary for those involved with SM to agree on a single definition, or how SM relates to advanced manufacturing, it is important for those in collaboration to be clear about how they understand the term(s) so as to avoid confusion and enhance their collaborative work. With this in mind, and for the purpose of this project, this report has adopted the following definition for SM based on one used by the United States-based National Institute of Standards and Technology (NIST) [4]:

- SM involves the use of advanced technologies such as the Internet of Things (IoT), AI, and Big Data analytics to optimize manufacturing processes and improve productivity and efficiency. This approach enables real-time data collection and analysis, facilitating informed decision making and predictive maintenance.

3.1.2 Technologies and Trends in SM

The manufacturing industry today is being rapidly transformed by new technologies and trends broadly related to the following:

- connectivity, which ensures seamless integration and communication across various systems and processes;
- intelligent automation, which is leveraging AI and robotics to enhance efficiency and precision, and is leading to smart(er) operations; and
- scalable data management and analytics, which allow manufacturers to manage vast amounts of data for insights that support strategic decision making and continuous improvement efforts.

For manufacturers to thrive amidst rapid industrial evolution, they must be familiar with trends in the sector and open to exploring and potentially adopting new technologies. A synopsis of some of the most important SM trends and technologies follows below.

3.1.2.1 Internet of Things

IoT refers to a network of physical devices, vehicles, appliances, and other objects embedded with sensors, software, and connectivity that enables them to collect and exchange data [5]. In the context of SM, IoT facilitates the connection and communication of various devices and systems on the factory floor, enabling enhanced automation, data analytics, and decision making. IoT devices help monitor and control equipment, automate processes, and provide insights into performance and health [6]. IoT sensors can predict equipment failure by monitoring machine health and usage patterns [7]. The sensors can also detect anomalies in the production process early, ensuring high quality by identifying defects before they escalate. IoT devices and applications can also track environmental conditions to ensure compliance with safety measures and monitor and optimize energy usage leading to reduced costs and sustainability [8].

Moreover, IoT enables end-to-end visibility of the supply chain, improving inventory management, logistics, and demand forecasting through real-time tracking and analytics. It allows manufacturers to quickly adjust production lines and processes to meet changing demands and customize products to individual specifications. It enables the collection of vast amounts of data that can be analyzed to inform strategic decisions, improve processes, and drive innovation. The International Data Corporation estimated in 2019 that the global manufacturing sector invested close to US$200 billion in IoT spending that year [9]. Despite the numerous advantages of IoT, there are some significant challenges that require attention, such as issues in integrating devices from various vendors due to a lack of standardization. Another challenge is ensuring safe and secure communication among devices [10].

3.1.2.2 Artificial Intelligence, Machine Learning, and Big Data

Machine learning (ML) is one approach used to achieve AI. ML is a major component driving modern AI advancements, although AI can be created without ML. Simply stated, the term AI refers to the broad concept of machines being able to carry out tasks in a way that humans would consider smart. AI encompasses a range of technologies and methods that enable machines to mimic human intelligence (e.g., robotics, automation, natural language processing). On the other hand, the term ML refers to a subset of AI that focuses on the notion that machines can learn from data. Instead of being explicitly programmed to perform a task, ML algorithms improve a machine’s performance as it is exposed to more data (i.e., statistical techniques are employed to give it the ability to “learn” from data). Big data refers to the large datasets—those that are too complex for traditional data processing systems—that serve as the “data fuel” for training ML models.

In an SM context, a vast amount of data related to production, quality, and performance is often produced by sensors and machines in the production system. The output from these sensors and machines can be used to create predictions, simulations, and more intelligent systems overall. ML algorithms use this Big Data to identify patterns and insights that would be difficult or impossible to discern manually. Many ML models and systems are specifically designed to handle and learn from Big Data. The combination of Big Data and ML drives innovation in SM by uncovering new insights, trends, and opportunities. It can enable predictive maintenance in SM [11]—by analyzing sensor data, machinery failures can be predicted before they occur. It can improve quality control and defect detection, which enhances quality and reduces waste. It can also optimize supply chain efficiency [12]—by forecasting demand, optimizing inventory levels, and streamlining logistics, lead times can be reduced, inventory costs can be lowered, and overall responsiveness to market changes can be enhanced [11, 12].

"The global Big Data analytics market size was valued at US$307.51 billion in 2023, and it is projected to grow from US$348.21 billion in 2024 to US$924.39 billion by 2032” [13]. Technologies that can quickly process large datasets to inform production, support quality control, and optimize performance are major enablers for the SM sector. A digitally enabled factory that is armoured with data analytics capabilities, AI, ML, and other relevant technologies can potentially deliver significant value. It can result in 30–50% lower machine downtimes, a 10–30% increase in throughput, a 15–30% increase in labour productivity, and 85% more accurate forecasting [14]. Clearly, the use of AI, ML, and Big Data is offering many important benefits to the economies of jurisdictions hosting SM industries. Many companies have experienced significant success as well. For instance, using ML, General Electric (GE) trained a surrogate model to evaluate a million variations of a design in a span of just 15 minutes. This enabled GE to cut the time it took to introduce a new product to market by half. Automation of this critical design review process allowed GE to dedicate more time to new design creation [15].

3.1.2.3 Automation and Robotics

Automation technologies are becoming widely used in manufacturing to enhance productivity, efficiency, and flexibility. Technologies, including robots, computers, advanced control systems, and interconnected networks of machines, have led to the development of "smart factories" that are able to ameliorate risk and effectively adapt to changing production demands [16]. These technologies have changed the way in which many facilities operate today [17], allowing them to become "smarter" facilities. Robotics and other forms of automation have unquestionably reduced the need for human-centricity in manufacturing [18]. They have even led to the emergence of "dark factories" (i.e., manufacturing facilities that can operate continuously (24/7) with minimal human intervention) [19].

Smart and dark factories can ultimately lower production costs, enhance productivity, and improve product quality [19]. Human-robot collaboration could help make production more agile [20]. Dark factories can also help manufacturers in jurisdictions struggling with labour availability issues [19] such as those prevalent in demographically aging nations, including Canada [20]. Moreover, they can help manufacturers deal with unanticipated disruptions such as the health-related disruptions caused by the COVID-19 pandemic [21]. Indeed, automated manufacturing facilities were less vulnerable to and affected by employee absenteeism caused by COVID-19 than those relying on human workers. In SM today, industrial robots—automated machines designed to perform repetitive tasks with precision and speed, such as assembly, welding, material handling, and packaging—are becoming increasingly popular in manufacturing. As with many other forms of automation, robots reduce the need for human labour, improve overall efficiency, and allow for product development flexibility.

Robots can and do work alongside and collaborate with humans in shared workspaces. They can assist with tasks that require human dexterity, decision making, and interaction such as quality control and small-scale assembly [22]. As industries pivot toward Industry 4.0 approaches and undertake automation at various levels, new models of advanced robotics are being introduced regularly. Indeed, the global population of operational industrial robots is growing by about 14% annually, and advancements in automation are leading to the development of new, more functional and versatile robots [23]. However, deployment of qualified workers capable of operating and working in sync with robots is viewed as a potential roadblock to continued growth in the development and use of robotics. A 2021 skills gap study by Deloitte and the Manufacturing Institute reports that four million manufacturing jobs will need to be filled in the United States alone between 2020 and 2030, and an estimated 2.1 million of these jobs will go unfilled due to the unavailability of qualified workers [24].

3.1.2.4 Additive Manufacturing

Additive manufacturing allows for the creation of highly complex geometries. It gives designers great freedom to create highly optimized and customized products with improved functionality, lightweight structures, and integrated features. Moreover, the time required to produce prototypes and final products through additive manufacturing is significantly reduced when compared to many other typical manufacturing processes. This enables quick design refinements and fast responses to market demands overall, thereby accelerating product development and production cycles. While the initial cost of investment in additive manufacturing technologies can be high, significant cost savings can be realized in the long term via reduced waste, as well as lower costs related to storage and inventory [25, 26].

3.1.2.5 Augmented Reality

Augmented reality (AR) is a technology that overlays digital information onto the real world, enhancing the perception of reality rather than replacing it. This can include adding 3D models, images, videos, or other digital content to the view of the physical environment [27, 28].

AR works through devices equipped with cameras, sensors, and displays such as smartphones, tablets, or AR glasses. These devices capture the real world and then integrate digital content into the scene, creating an interactive and immersive experience.

3.1.3 The Evolution and Relevance of Smart Manufacturing

The evolution of traditional manufacturing into SM marks a revolutionary shift in the global industrial landscape [29]. Traditional methods that rely heavily on manual labour, linear production processes, and limited connectivity between different stages of production are becoming a thing of the past. The development trajectory of SM has been marked by numerous milestones and collaborative efforts. The early 2000s witnessed the development and widespread adoption of IoT technologies, including smart sensors, wireless sensor networks, Bluetooth, smart grids, and machine-to-machine communication, which, in part, laid the foundation for SM. By the mid-2000s, the term "smart manufacturing" had gained prominence among industry experts. Entities such as the Smart Manufacturing Leadership Coalition in the United States and Industrie 4.0 in Europe were formed. They brought together various actors to accelerate the implementation and document the progress of SM [30].

Looking ahead, by 2030, demand for industrial SM-related systems and solutions is expected to have a compound annual growth rate of 7.4% (see Table 1). As of 2022, the annual growth rates for augmented reality/virtual reality solutions, AI/machine learning solutions, and nanotechnology solutions are expected to be in the range of 39%, 38%, and 35% respectively. The growth and use of solutions related to IoT (23%), additive manufacturing (21%), biomanufacturing (12%), industrial lasers (10%), and industrial cleantech solutions (5%) are all also expected to grow [31]. Clearly, in today's rapidly changing technological landscape, SM is becoming increasingly important. The numerous advantages and benefits of SM technologies and systems, including increased efficiency, enhanced quality control, reduced costs, lessened waste, agility, and the flourishing of innovation, are now well known and widely accepted. By harnessing the potential of SM, manufacturers can optimize operations, lower production costs, strengthen competitiveness, create new opportunities, and maintain resilience in the face of market disruptions [32].

3.2 The Growing Importance of SM: Key Benefits

There is an increasing awareness amongst industry leaders that SM adoption will be key to their companies' future success. According to a 2024 State of Smart Manufacturing Report by Rockwell Automation that surveyed over 1,500 manufacturers across 17 leading manufacturing countries [33], 95% of manufacturers surveyed were using or evaluating the use of SM technology (up from 84% in 2023), 94% of them were planning to maintain or grow their workforce due to SM technology adoption, and 83% were expecting to use generative AI in their operations in 2024. Some of the most important benefits that accrue to companies that adopt SM, and that are cited in this report and other available documents, are noted below:

Table 1: Expected Annual Growth Rate (2030) For Different Types of SM Solutions[1]

SM Solutions	Expected Annual Growth Rate
Overall demand for industrial automation systems	7.4%
Augmented reality/virtual reality solutions	39%
AI/machine learning solutions	38%
Nanotechnology solutions	35%
IoT	23%
Additive manufacturing	21%
Biomanufacturing	12%
Industrial lasers	10%
Industrial cleantech solutions	5%

[1] Next Generation Manufacturing Canada [31]

- **Enhanced safety** – SM integrates safety protocols and real-time monitoring to create safer work environments. SM technologies, such as robots, are equipped to handle tasks that require the handling of hazardous materials, combustible items, or toxic chemicals. Sensors and monitoring systems can also identify potential dangers—and notify human workers—which can help to prevent accidents and reduce the number of emergencies, thus lowering the overall risk for factories [34].
- **Cost reductions** – SM technologies could enable organizations to identify cost-saving opportunities through data analysis and process optimization. This could help smart factory managers predict and resolve maintenance issues better and faster, thereby reducing downtime [35].
- **Enhanced productivity and efficiency** – SM can help to streamline and optimize processes by providing seamless data on maintenance, potential bottlenecks, and other inefficiencies. Data can be used to reduce production times, minimize waste, increase throughput, and enhance overall productivity. According to a 2019 report by Deloitte and the United States-based Manufacturers Alliance for Productivity and Innovation, SM technologies have enabled some factories to make gains of between 10–12% in areas of labour productivity, output, and factory utilization [35].
- **Improved quality** – By implementing SM technologies, such as real-time monitoring, predictive analytics, and advanced quality control systems, enterprises can potentially identify and rectify issues in the production process in real-time. They can detect defects early on in a process, and therefore help ensure higher product quality and customer satisfaction. Smart technologies that rapidly detect errors and defects save businesses time and money. They can help reduce the need for human intervention; this serves to reduce human error, which can negatively impact quality [33, 36].
- **Innovation and product development** – SM technologies that facilitate rapid prototyping and enable iterative design processes via digital twin technology and collaborative platforms can help accelerate innovation cycles and time-to-market [36].
- **Increased flexibility and customization** – SM systems are highly adaptable and can be reconfigured to accommodate changes in demand and in product specifications [36]. This helps manufacturers respond rapidly to consumer needs/demands and reduce time-to-market [37]. Since SM technologies follow a predictive maintenance model, the availability of real-time data on equipment operations may help prevent unplanned machinery breakdowns and improper maintenance, which can lead to both downtime and increased stress in the workplace [38].

- **Customization and personalization** – SM harnesses technologies that can efficiently offer customizable products tailored to individual customers. Faster response times and improved customer service made possible via SM can lead to enhanced customer experience overall [39].
- **Improved supply chain management** – SM can help enable seamless integration and coordination with suppliers, distributors, and other stakeholders across the supply chain. This improves inventory management [10] as real-time machine-level data from a network of suppliers spread across various geographies can help manufacturers more effectively deal with load balancing and capacity planning. Integrating SM technologies with supply chain management systems can also improve visibility, traceability, and responsiveness across a supply chain network [40].
- **Reshoring related to expanding manufacturing capabilities and building a skilled workforce in SM** – As many countries have lost manufacturing assets to lower-cost competitors, SM can help to reverse that trend via "reshoring", which is the practice of bringing production sent abroad back to the country of origin. This approach can help address trade and budget deficits, and build a skilled workforce in SM [41].
- **Easier and faster access to essential parts/ materials** – By implementing SM technologies, such as additive manufacturing, into factories, companies can ensure that parts can be created when and where they are needed [26].
- **Enhanced sustainability and environmentally conscious practices** – Companies that adopt sustainable or green SM technologies and practices, including using renewable energy sources to reduce carbon footprints, can potentially minimize their environmental impacts overall [42, 43, 44]. They could also gain a competitive advantage in the marketplace that comes from being characterized as an environmentally conscious manufacturer.

3.3 Global Adoption of SM: Industry Leaders and Growth Drivers

The global adoption of SM is being led by various industries. Some of the more prominent industries at the forefront of this trend are the automotive, aerospace and defence, information technology, and pharmaceutical industries.

The automotive industry is actively embracing SM technologies to improve efficiency, enhance product quality, and optimize supply chain management. According to a market study by Grand View Research, the automotive industry represented 24% of the SM market worldwide, and it is expected to grow at a compounded annual growth rate (CAGR) of 15.6% from 2023 to 2030 [45].

Similarly, the aerospace and defence industry has been quick to adopt SM technologies due to the industry's complex manufacturing requirements. These technologies help enhance productivity, ensure precision, and improve maintenance and repair operations. This industry's share in the SM sector is expected to grow at a CAGR of 16.6% from 2023 to 2030 [45].

In the information technology sector, the adoption of cloud computing, digital technologies, cybersecurity solutions, automation, and other innovative technologies, such as augmented reality, virtual reality, machine learning, and AI, is driving rapid growth. According to a 2024 market research report by Grand View Research, the size of the global information technology services market in 2023 was US$1.36 trillion, and it is expected to grow at a CAGR of 9.5% from 2024 to 2030 [46].

The pharmaceutical industry also leverages SM technologies and processes to improve the efficiency and optimization of its development, production, and distribution systems. These technologies ensure regulatory compliance and enhance supply chain efficiency and visibility. The global pharmaceutical market size in 2022 was estimated at US$1,482 billion, and it is expected to grow at a CAGR of 6.12% from 2023 to 2030. The industry's orientation toward Pharma

“The automotive industry is actively embracing SM technologies to improve efficiency, enhance product quality, and optimize supply chain management.”

4.0, which includes the use of robotics, AI, IoT, cloud computing, Big Data analytics, and other technologies, explains its growth and success as SM technologies enable companies to improve efficiency, reduce costs, and ensure product quality [47].

The adoption of SM technologies has been significantly influenced by a variety of growth drivers, which continue to propel their integration across various nations and industries. Various factors have driven, and are continuing to drive, the global growth of SM technology adoption. These factors include the need for increased efficiency and productivity, growing demands and requirements for customization, and the need for enhanced product quality and consistency. The rapid shift from traditional manufacturing approaches to smart(er) ones over the past decade can also be directly linked to advancements in key technologies such as IoT, AI, Big Data analytics, and robotics [48]. The increasing relevance of sustainable and environmentally sound practices has also pushed many corporations to adopt cleaner and greener SM technologies. In the years to come, the further development of technologies that allow for faster connectivity and improved reliability and security between SM systems, such as 5G, will continue to drive growth in SM technology adoption [49, 50].

Notwithstanding recent and anticipated growth in SM, challenges to adoption remain:

- Data security and privacy concerns involve addressing cybersecurity threats and ensuring the protection of sensitive data in interconnected manufacturing systems [51]. In 2024, the global average cost associated with a corporate data breach was US$4.88M, a 10% increase over 2023, and the highest total ever [52]. The costs incurred were related to detecting and addressing breaches, financial losses due to downtime and reduced revenues, legal fees, and lasting harm to a company's reputation and brand. Cybersecurity measures are vital for SM as they ensure the secure operation of critical systems. They protect sensitive data, safeguard intellectual property, and enhance operational resilience. By investing in cybersecurity, manufacturers can ensure that their operations are well-protected against possible attacks that can have dramatic financial, legal, and reputational consequences. For instance, the Japanese car manufacturer Honda suffered a cyberattack on its global operations in 2020. This led to a temporary shut-down of Honda’s production facilities across the globe, including in the United States and the United Kingdom. It brought critical functions, such as customer and financial services operations, to a complete halt [53].
- Interoperability issues arise from integrating diverse systems, technologies, and equipment from different vendors to enable seamless communication and collaboration [54].

- Skill gaps and workforce training are necessary to upskill workers to operate and maintain advanced manufacturing technologies such as robotics, AI, and IoT [55].
- Cost and return on investment (ROI) concerns involve balancing the upfront investment required to implement SM technologies with the expected ROI [56].
- Legacy systems integration requires retrofitting existing infrastructure and equipment with SM capabilities while ensuring compatibility with legacy systems [57].
- Regulatory compliance involves navigating regulatory frameworks and standards related to safety [20], data privacy, product quality, and environmental sustainability.
- Supply chain disruptions involve managing risks associated with global supply chains, including dependencies on critical components and geopolitical factors [58].
- Ethical and social implications include addressing ethical considerations such as job displacement, algorithmic bias, and environmental impact associated with SM [59].

3.4 Environmental, Social, and Governance Factors

Leading-edge SM companies are concerned about how their practices and technologies impact society, nature, and sustainability. These companies and the agencies that monitor them and their impacts, use various environmental, social, and governance (ESG) criteria to measure performance, correct practices where necessary, and manage overall impact. They do so to meet growing consumer demand for products that have been manufactured in a responsible and sustainable way. Not all companies are addressing their ESG issues to the same degree or in the same way. Indeed, in the SM ecosystem there are both leaders and laggards. However, most understand that increasing consumer and government regulator demand for socially and environmentally responsible corporate behaviour is likely here to stay [60]. In the future, governments are widely expected to implement new, more, and more stringent environmental and other regulations for manufacturing businesses.

Given this emerging reality, there is a growing interest in, and an increased focus on, how technologies can be made both smarter and greener, and how they can be used to protect, preserve, and even repair natural systems. The term “greentelligent” has been coined to describe companies that are able to use eco-friendly processes and smart technologies to achieve greater productivity outcomes, while meeting corporate and societal sustainability goals and targets [61].

Some of the ways in which SM companies today are responding to these ESG-related expectations and/or requirements include using IoT technologies to enable real-time data collection, which then allows for the continuous monitoring of environmental impacts. For instance, smart technologies can be used to continuously monitor and optimize energy usage within a manufacturing facility or process, thus leading to lower greenhouse gas emissions. In addition, the precise production techniques associated with SM not only use fewer natural resources, including water, compared to traditional methods, but also could potentially produce less waste per unit.

Moreover, SM not only promotes the recycling and reuse of materials via advanced sorting and processing technologies but it also applies data analytics to product design processes to ensure new products are easy to recycle [62, 63]. SM can also help to achieve the sustainability goals of a social-good and good corporate governance nature because smart technologies and processes can be used to monitor worker health and safety in real-time, thus reducing and mitigating risks for workers. Smart automated processes can also be used to reduce worker fatigue. Through Big Data analytics, SM systems can help to monitor, verify, and report on the ethical sourcing of materials used in manufacturing processes. This can help to improve corporate compliance with labour laws, ethical standards, and human rights laws. Finally, digital tools that provide real-time data can also lead to better corporate decision making, enhanced transparency and accountability, and stronger relationships and trust with customers, investors, and the general public [64].

3.5 Evaluating Global SM Practices: A Focus on the United States, Germany, and Singapore

For this project, the United States, Germany, and Singapore were selected as SM jurisdictions because they are viewed as leaders in today's global SM ecosystem. To enhance their manufacturing processes, products, and services, they have invested heavily in the development and adoption of various advanced and smart technologies, including AI, robotics, cloud computing, and Big Data.

More specifically, the United States was included here because of its significant importance to Canada as its largest trading partner, its extensive adoption of SM practices, and the availability of United States-based industry data related to SM. Germany was chosen because of its manufacturing-driven economy, its notable progress in implementing SM technologies, its abundant data resources, and its global leadership with both SM implementation and standards development. Singapore was selected because of its highly advanced manufacturing sector, the rapid pace at which it is adopting Industry 4.0 solutions, and because it is situated within the Asia-Pacific region, the world's most advanced SM region.

3.5.1 SM in the United States

With 15.9% of global manufacturing output, the United States is the second largest manufacturing country in the world after China [65]. Both the United States and China can be considered early SM adopters. Moreover, the United States is home to some of the world's major automotive players that are investing large sums in electric vehicle innovation, development, and production, including self-driving technologies. Further to this, the United States is also home to a competitive semiconductor industry that employs nearly a quarter of a million workers [66]. Broadly speaking, SM development efforts in the United States have been led by the private sector [67]. In more recent times, however, the United States government has shown considerable interest in becoming more deeply involved with industrial policy related to Industry 4.0 matters. For instance, the United States semiconductor industry is supported by the $50 billion CHIPS for America program, the largest federal industrial policy push in decades. This program includes subsidies for chip production, efforts to enhance U.S. leadership in R&D, tax credits for smart equipment investment, and $28 billion in federal funding to develop domestic capabilities for advanced logic and memory chip production [68].

Other efforts on the part of the United States federal government to strengthen SM across America have also been made over the years. For instance, the 2015 Smart Manufacturing Leadership Act sought to improve the productivity and energy efficiency of the manufacturing sector by directing the Secretary of Energy to provide SM-related assistance to small and medium-sized enterprises (SMEs). In 2019, an amended version of the Bill was reintroduced in the Senate. This version sought to improve the productivity and energy efficiency of the manufacturing sector by developing a national smart manufacturing plan and by assisting small and medium-sized manufacturers. Another version of this Act, with similar aims as both of the past efforts, was also brought to the Senate in 2021 (S.3120) where it was read twice before being referred to the Committee on Energy and Natural Resources, where it currently resides [69]. Although never ratified, the various iterations of this Bill have likely raised awareness among legislators about the importance, value, and potential of SM.

These and other legislative and executive initiatives advancing SM adoption in the United States have been supported by the work of various federal agencies and departments. For instance, in 2015, the Department of Energy announced investments of US$70 million for the establishment of an SM-focused Clean Energy Manufacturing Innovation Institute [70]. More recently, in 2022, the United States government, through its National Science and Technology Council, released the National Strategy for Advanced Manufacturing. The strategy generally aims to provide leadership for and across the SM sector, and specifically promotes communication, coordination, and collaboration across agencies and stakeholder groups [71]. Further to this, in March 2024, the Department of Commerce's NIST

announced an open competition for a new institute focused on using AI to improve the resilience of United States manufacturing. This AI institute will become part of Manufacturing USA, a network of 16 institutes that connects people, ideas, and technologies in support of SM. NIST expects to invest US$70 million in federal funds into this institute over the next five years, with matching or greater contributions from private and other non-federal sources [72].

Even with its national strategy for advanced manufacturing, the United States has no national standards development strategy. Its standardization community follows a decentralized, market-driven approach that is supported by independent, private-sector standards development organizations (SDOs) [67, 73]. Notwithstanding this, there are various standards-related initiatives led by multiple groups and organizations, including government organizations, such as NIST, and non-profits, such as the Clean Energy Smart Manufacturing Innovation Institute (CESMII: The Smart Manufacturing Institute), which is one of 16 institutes operating as part of the Manufacturing USA network [74]. Some sector observers believe that the lack of government involvement when it comes to SM standards means that the United States might not effectively lead the development of standards internationally [67, 75].

According to the Capgemini Digital Transformation Institute, the United States leads when it comes to smart factory implementation. In its 2017 Smart Factory Survey, the Institute reported that 54% of United States manufacturing companies were actively involved with an ongoing smart factory initiative. By comparison, in Germany, only 46% of manufacturers had a smart factory effort underway at that time [76]. The high level of SM implementation activity reported by the Capgemini survey underscores the competitiveness and innovation potential of the United States technology and manufacturing sectors. There are many examples where companies have been actively implementing Industry 4.0 solutions into their workflows. For instance, Ericsson US's 5G smart factory in Lewisville, Texas, which cost US$100 million, was recognized by the World Economic Forum in 2021 as a global front runner in the Industry 4.0 revolution [77]. In 2016, Faurecia's invested €57 million in a smart factory in Columbus, Indiana, using digital technologies, such as automation and data processing, to advance the company's SM agenda [78].

The Smart Manufacturing Cluster of Northeast Ohio is another example of SM leadership in the United States. This collaborative network involves more than 150 industry leaders, non-profits, community groups, and other stakeholders, and it has a mission to create thousands of jobs, transform the manufacturing industry in the United States, and "lead the world in smart manufacturing" [79]. Notwithstanding these SM developments, and the fact that the United States clearly wants to re-establish itself as a major manufacturing nation and be a global leader in SM [67], some observers believe countries where governments play a more active role, especially regarding standards, will emerge as the true global SM leaders [75]. Still, recent legislative and executive initiatives in the United States related to an Industry 4.0 strategy have led some other foreign policy and economy analysts to argue that industrial policy is in fact making a comeback in the United States. They cite recent executive industrial policy efforts related to SM, such as the Manufacturing USA initiative and the *CHIPS and Science Act* [68], and note that when it comes to SM, the United States government is no longer as passive as some might believe.

3.5.2 SM in Germany

Manufacturing is one of Germany's main economic pillars. According to the World Bank, in 2023, manufacturing's share of Germany's national economy was 18.96%, one of the highest percentages in the world [80]. By comparison, manufacturing contributes 9%, 11%, and 18% respectively to the Canadian, American, and Singaporean economies [81]. Supporting the development of the manufacturing sector, and SM in particular, has been a key focus for successive German governments over recent decades. In Germany, 75% of companies across various industries have adopted digital solutions, with approximately 15 million employees directly and indirectly engaged in advanced manufacturing sectors [82]. While private entrepreneurship plays an important role in the German economy, the German government also takes an active role in supporting the SM industry through regulation, incentives, and other supports informed by significant input from stakeholders [67]. In 2015, the German government, through its Ministry of Education and Research and Ministry for Economic Affairs and Energy, launched its Industrie 4.0 program, a strategy that is shaping the digital transformation of the manufacturing sector [83]. Through this and other initiatives, Germany largely consolidated its status as a global manufacturing and SM powerhouse.

Today in Germany, Industrie 4.0 continues to be considered a key target of government strategic economic and industrial policy [84]. SMEs, large corporations, and other stakeholders can apply for SM-related funding through various government ministries. This federal funding complements private investments in Industrie 4.0 technologies. For example, to support the federal government's Digital Agenda, two Industrie 4.0 funding programmes—Autonomics for Industrie 4.0 and Smart Service World [85, 86]—provide close to €100 million for research and innovation initiatives related to SM. Moreover, regional Mittelstand 4.0 Centres of Excellence, such as the Mit uns digital centre serving Lower Saxony and Bremen, support SMEs with SM information, training, and resources, including testbeds [87].

In addition, universities, research centres, and institutes receive support through federal and state government grants. For instance, in 2023, the Fraunhofer Institutes —one of the largest networks of research centres in the world—received about one-third of its research funding from the German federal and state governments. In addition to this regular base funding, additional research funding amounting to €249 million was also provided [88]. These institutes are a major driver of innovation in Germany. They remain the leader among German research institutions in terms of annual number of invention disclosures and new patent applications. In 2023 alone there were 506 inventions and 406 patent applications made that year. The overall Fraunhofer portfolio of active patent families, each of which comprises intellectual property rights in different countries, stands at 7,068 [89]. Today, the Institutes have even become a role model for Manufacturing USA [90]. Many other SM-related organizations also receive funding from the German government. For instance, in 2022, funding for research into the future use of AI was significantly boosted when five German AI competence centres, previously funded as projects for a limited period, were made permanent with institutional funding (up to €100 million annually) from the Federal Ministry of Education and Research and participating German states. The aim of this support is to establish Germany as a leading location for research, teaching, and technology transfer related to AI [91].

Germany is also a global leader when it comes to SM-related standards development. One key reason is that there is a high degree of coordination and collaboration within and across the German manufacturing sector. This collaborative environment makes it possible, and easier, to develop standards that are acceptable to multiple German stakeholders. It also allows Germany to speak with one voice internationally, which has helped to establish Germany a global leader when it comes in Industry 4.0 standards development [75]. Another reason for this leadership is that in Germany both the private sector and government play proactive roles in the standards development process. Each sector brings its unique strengths to the standardization challenge, and there is effective communication between sectors. Some consider this to be Germany's SM competitive advantage [67]. In addition to this, Germany's overall collaborative approach to SM standards development is further strengthened by the presence of three unique entities that form a type of "triangle for standardization" in that country:

- **Platform Industrie 4.0:** This network, formulated by the German government has six working groups focusing, among other things, on strategy and leadership related to standardization. The network does not develop standards but rather coordinates the efforts of member organizations [84].
- **Standardization Council Industrie 4.0:** This Council represents the interests of industry. It is independent from the Platform but follows its strategies and guidance. The Council also plays a coordination role by keeping track of all the activities running in parallel across all relevant international organizations. It does this to ensure German efforts are aligned with international efforts, thus preventing unnecessary duplication and other inefficiencies from arising [92].
- **Labs Network Industrie (LNI 4.0):** This network helps companies to enhance the quality of their products. The German use-case test validation process—a unique standardization process that ensures companies can successfully test and then implement standards—was developed by LNI 4.0 with public funding. LNI 4.0 also supports SMEs that have limited research and development (R&D) budgets [93].

In addition to the various funding and other supports provided by the German government for standardization initiatives, the German government also sometimes puts pressure on companies to develop and agree to common standards. It does this by implicitly threatening to introduce mandatory regulations if standardization efforts fail. According to some observers of German standardization efforts, this is one of the main driving forces for standardization co-operation and success in Germany. In the eyes of the German government, although the "carrots" of encouragement, funding, and other supports are essential for standards development and adoption, so too are the occasional "sticks". Regarding the latter, as of 2017, more than 8,000 standards were directly cited in German legislation, which means that companies are required by law to adopt them [75]. Regarding international co-operation and collaboration, the German government and the Platform co-operate with China, Japan, and South Korea. Through joint committees and other means, Germany works with these nations to coordinate their respective positions and activities related to international standardization.

On the industry side, investment in SM is rapidly growing in Germany. Between 2015 and 2020, industry had invested more than €10 billion in Industry 4.0 solutions [94]. To facilitate research and pool resources, German companies have also formed superclusters. For instance, OWL, one of Germany's leading technological superclusters, brings together over 180 companies, universities, research institutions, and economic collaborative initiatives based in the Ostwestfalen-Lippe region to work together on the development of SM innovations. Its membership includes representatives from mechanical and electrical engineering, computer science, and automotive supply industries. In addition to these collaborative initiatives, there are also many examples in Germany of individual companies investing heavily in SM technologies over the past decade. For example, in a Siemens smart plant in Amberg, Germany, machines and computers were independently handling 75% of the company's value chain as early as 2017 [76].

"As with Germany, Singapore's government is striving to transform its economy into one that is innovation-led."

3.5.3 SM in Singapore

Manufacturing constitutes a major part of Singapore's economy [95]. In 2022, the manufacturing sector contributed 21.6% to Singapore's nominal gross domestic product (GDP) [96]. The country is one of the leading manufacturing hubs in Southeast Asia and one of the world's largest exporters of high-tech goods. Singapore is among the world's top 10 exporters of machinery and equipment. In addition, it produces 60% of the world's micro-arrays, one-third of the world's mass spectrometers, and 4 of the top 10 drugs by global revenue [97]. Singapore's government has been heavily involved in enabling manufacturing innovation and growth. Given the manufacturing sector's importance to the country's economy, its government has been an active promoter and supporter of R&D and other innovation activities related to SM [95]. As with Germany, Singapore's government is striving to transform its economy into one that is innovation-led. Its budgetary spending on manufacturing-related R&D has increased steadily over recent years. In an ongoing effort to build a more sustainable and resilient sector, Singapore released its Manufacturing 2030 vision in 2020 [98]. The plan aims to double the size of the sector by helping firms upskill their workers, in collaboration with educational institutions, so they can move into more specialized roles important for SM. It also seeks to continue attracting top-tier global and local businesses, and enhance efforts to develop the capabilities of local businesses, thereby creating better job opportunities [98].

More recently, in Singapore's Budget 2023, the country introduced an Enterprise Innovation Scheme (EIS) that encourages businesses, including those involved in SM, to engage in innovation and R&D. The EIS enhances existing tax measures and introduces new ones for qualifying companies. Those undertaking R&D activities now enjoy a 100% tax deduction for all qualifying expenditures incurred on these projects. Further to this, through Budget 2023, the Singapore government now offers generous tax deductions related specifically to training. For courses approved by SkillsFuture Singapore—a government-supported entity that provides opportunities for skills enhancement while also helping to drive the growth of the national economy [99]—companies can enjoy a tax deduction of 400% for the first US$298,000 spent on training [100]. There is also a special tax deduction for innovation projects carried out with Singapore's Institute of Technical Innovation or other qualified partners. Further to these incentives, innovators, including SM technology developers, can now enjoy a 100% write-down allowance on capital expenditures related to intellectual property rights, and a further 200% tax deduction on the first US$74,600 spent on expenditures related to the licensing of those rights [100].

The Singapore government has taken other steps to support Industry 4.0 implementation and the manufacturing industry more broadly. It partnered with industry to conduct a nation-wide assessment of the skills needed for future labour force of the future.

It launched the SkillsFuture Series for Advanced Manufacturing, a training program to help build up new engineering and technology skills across the nation. In collaboration with unions and companies, information sessions and workshops on Industry 4.0 matters are offered regularly. Singapore has also established several national SM support initiatives, including the National Robotics Program, which exists to help companies integrate robots into their factories, and the National Additive Manufacturing Innovation Cluster, which has, among other efforts, supported the development of 3D printing. Moreover, with the support of government, model factories have been built in Singapore's research institutes and universities to create spaces where new technologies can be tested [101].

In addition to these initiatives, Singapore's government, in conjunction with the nation's Economic Development Board, developed the Singapore Smart Industry Readiness Index. This is the first tool developed by a government to support the national transformation of its manufacturing and industrial sectors. The index serves as a tool for companies to evaluate the Industry 4.0 readiness of their facilities, and to help them strategically plan for the implementation of new technologies [96, 97]. Moreover, the government also hosts the Industry Transformation Asia Pacific annual regional "platform" or forum that brings together stakeholders from governments and industries in the Asia-Pacific region involved with the digital transformation of the manufacturing sector.

Regarding SM standards-related activity in Singapore, all matters related to standardization in this nation are ultimately guided by Enterprise Singapore, the country's national standards and accreditation body. Broadly speaking, Enterprise Singapore—a government entity—collaborates with industry and other stakeholders to expand markets, advance innovation, and ultimately grow the economy [102].

Enterprise Singapore administers the Singapore Standardization Program through an industry-led Singapore Standards Council (SSC). The SSC approves the establishment, review, and withdrawal of standards and technical references in use in Singapore. It also advises Enterprise Singapore on the policies, strategies, initiatives, and procedures for standards development and promotion [103]. Generally, Singapore's national standards policy is focused on building a robust and high-quality standards ecosystem that helps companies enhance the quality of their products and services. It is also focused on facilitating access to markets, improving public health and safety, and protecting the environment for all Singaporeans. Overall, Singapore's commitment to innovation, technology advancement, and SM is mirrored in its early adoption of existing international standards of relevance to SM, as well as by its participation in the development of new ones. Singapore is also represented through the SSC on key international standards organizations such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) [103].

In summary, the United States, Germany, and Singapore are recognized as leaders in today's global SM ecosystem. These countries consistently invest in innovation, sustainability, and workforce development, propelling the evolution of manufacturing practices worldwide. The upcoming section will explore the Canadian SM landscape, followed by a comparative analysis with these international markets, offering valuable insights for Canada's manufacturing sector.

3.6 The Canadian Smart Manufacturing Landscape and Ecosystem

3.6.1 The Importance of SM in Canada

The manufacturing sector in Canada plays a crucial role in the country's economy. Two-thirds of Canadian goods exports are manufactured goods. The sector not only contributes significantly to the nation's GDP, but it is also a major employer, providing jobs to about 1.7 million people [104, 105]. Moreover, the manufacturing industry offers the highest total worker compensation of any industry in Canada. These facts highlight the sector's important role in supporting the livelihoods of many Canadians. Despite being challenged by the COVID-19 pandemic in 2020, over recent years, manufacturing in Canada has experienced remarkable growth and success. In 2021, the total revenue for Canadian manufacturing hit C$787.3 billion, marking an increase of C$108.9 billion (+16.1%) from 2020 and C$39.1 billion more than in 2019 [106].

Revenue from manufactured goods increased in 18 of 21 Canadian manufacturing subsectors. The largest increases were in petroleum and coal products (+C$25.1 billion), primary metals (+C$18.1 billion), wood products (+C$17.0 billion), food (+C$14.3 billion), and chemicals (+C$10.4 billion), all of which contributed C$84.9 billion to this annual increase [106]. In 2022, revenue from manufactured goods further increased 17.4% (+C$128.4 billion) to C$866.7 billion [107]. Overall, these statistics underscore the strength of the Canadian manufacturing sector [108]. They showcase how manufacturing thrives across different types of industries, and how no one industry dominates market share.

3.6.2 Leading Industries in Canadian Smart Manufacturing

When looking at Canadian industries that have successfully adopted SM technologies, the automotive, pharmaceutical, aerospace and defence (A&D), and food processing industries stand out as exemplars [109]. With one of the largest automotive manufacturing sectors globally, Canada is home to prominent auto companies operating on a national scale,and all of these companies have adopted SM technologies and processes. The pharmaceutical sector in Canada—a sector that has experienced impressive growth recently, driven in part by its ability to swiftly respond to national COVID-19 pandemic requirements—is also a leading national industry when it comes to SM. Further to this, Canada's A&D industry, the world's fifth largest, and Canada's steadily growing and highly competitive food processing sector, are also noteworthy adopters of SM. Insights into the general transformative power of SM, and how it has positively impacted manufacturing in Canada, can be gained with an understanding of how each sector has successfully harnessed the potential inherent in SM.

Canada is one of the world's top 12 producers of light vehicles. Five major OEMs assemble more than 1.4 million vehicles in Canadian plants each year. The sector contributed C$12.5 billion to GDP in 2020, and it is one of Canada's largest manufacturing sectors overall. The industry, which directly employs more than 117,200 people [110], increasingly integrates SM technologies into its workflows. The corridor from Windsor to Ottawa, which is home to the second-largest vehicle production cluster in North America, can certainly be considered a SM cluster. The modernization of manufacturing in this corridor has been and is financially supported by NGen, a national industry-led non-profit organization leading Canada's Global Innovation Cluster for Advanced Manufacturing [111].

Generally speaking, several primary SM technologies support and are employed in the automotive sector. The industry extensively utilizes robotics and automation for various manufacturing processes, such as welding, assembly, painting, and material handling. Robots enable precise and repetitive tasks, improving speed and accuracy while reducing human error. IoT technologies connect machines, devices, and sensors in the automotive manufacturing environment, enabling real-time monitoring of equipment performance, predictive maintenance, and data-driven decision making for optimizing production. The automotive sector harnesses data analytics and AI to analyze large amounts of manufacturing data and derive actionable insights. AI algorithms can optimize production schedules, predict quality issues, and enhance supply chain management. Additionally, additive manufacturing, or 3D printing, is increasingly used in the automotive industry for rapid prototyping, tooling production, and the manufacturing of end-use parts, enabling greater design flexibility, faster production cycles, and cost efficiencies.

The adoption of SM technologies in the automotive industry has resulted in tangible benefits for both customers and manufacturers. Specific examples of these benefits include reduced unplanned downtime, as tracking equipment performance and health optimizes maintenance, making these assets more reliable and available for use. By keeping equipment and production lines up and running, auto manufacturers see better end-production and reliability. Additionally, fewer inefficiencies are achieved by breaking down information and data silos, allowing automotive manufacturers to tap into previously unused or underutilized data, speed operations, and produce vehicles and parts faster and with greater precision. Furthermore, faster time to market is realized by integrating SM into production processes, increasing the speed at which vehicles reach markets. This is particularly necessary for unexpected demand surges, as seen recently in the electric vehicle market.

In addition to the automotive sector, Canada's A&D sector is one of the country's largest contributors to economic growth. In 2022 it employed over 200,000 Canadians, and Canada the only country in the world ranking in the top five nations across civil flight simulator, engine, and aircraft sub-segments [112]. Canada's A&D industry is globally renowned for its excellence in aircraft manufacturing and related technologies. The country is home to major aerospace companies like Bombardier, Pratt & Whitney Canada, and CAE (Canadian Aviation Electronics). The industry produces commercial and business aircraft, helicopters, and a wide range of aerospace components and systems.

As a sector, A&D in Canada is primed for growth and innovation through the adoption and implementation of new SM technologies. There are numerous SM applications relevant to A&D, including AI and ML, which are used during production processes where A&D systems require powerful algorithms to connect datasets and improve efficiency. These technologies play a crucial role in A&D manufacturing, especially regarding quality control, process optimization, and predictive maintenance.

Automation and robotics are employed in A&D manufacturing related to assembly, drilling, and inspection. They create considerable value for A&D processes given the sector's low production volumes and related low tolerance for error. Automation and robotics also help prevent human error, reduce labour costs, increase productivity, and augment human worker performance [113].

Additive manufacturing technologies can benefit the A&D sector in numerous ways. It is particularly useful for concept modelling, prototyping, tooling, and the fabrication of complex and/or low-volume parts. Through additive manufacturing, material costs and production times for aircraft parts can also be lowered.

IoT devices and connectivity are used to monitor and collect data from aircraft systems and components. Real-time data analytics enable predictive maintenance, reduced downtime, and optimized aircraft asset lifecycles.

Canada's highly innovative pharmaceutical sector is composed of companies that develop and manufacture cutting-edge medicines and medical devices. Pharmaceutical sales in Canada account for 2.2% of the global market, positioning it as the eighth largest market worldwide. In 2022, the manufacturing segment of this growing sector employed approximately 33,000 people. Some examples of Canada's leading pharmaceutical companies and their total 2022 sales include Johnson & Johnson (C$4.73 billion), Novartis (C$1.75 billion), AbbVie (C$1.71 billion), Novo Nordisk (C$1.62 billion), Astra Zeneca (C$1.48 billion), and Pfizer (C$1.46 billion) [114]. Overall, the pharmaceutical sector has been and is adopting SM technologies to streamline production, enhance quality assurance, and ensure regulatory compliance.

In the pharmaceutical industry, AI has become crucial. This was underscored during the COVID-19 pandemic when the importance of efficient supply chains was highlighted. AI, in the context of Internet-enabled process management, is being used to improve quality assurance and facilitate advanced data sharing, allowing for company-wide monitoring of drug production operations and processes [115]. Additionally, AI enables predictive and proactive manufacturing, allowing companies to forecast future drug demand, analyze potential supply chain bottlenecks, and adjust production accordingly [115, 116].

In addition, automated robots are a key component of Pharma 4.0, enhancing workplace health and safety by automating repetitive tasks and reducing worker exposure to toxic materials. These robots help minimize human error and prevent product failures [117]. These SM technologies have already been successfully implemented in the production lines of Canadian pharmaceutical companies. For instance, Sanofi's C$500 million vaccine factory in Ontario is equipped with various automation technologies. These technologies enable Sanofi to monitor its production line in real-time and perform preventive maintenance using data provided by sensors and processed via AI [118].

In 2022, the food and beverage processing industry was the largest manufacturing industry in Canada [119], accounting for 18.2% of the nation's total manufacturing sales and with the value of manufactured goods reaching C$156.5 billion [120]. In 2022 the industry also accounted for 1.7% of Canada's GDP [120]. The industry is Canada's largest manufacturing employer with 300,000 Canadians employed, and it is a major contributor to our national economy [120]. Canada is also the world's fifth largest global exporter of agricultural products [119], with food processing accounting for 90% of our export sales (around 90%), and beverage processing constituting the remainder [119]. This industry is important to all regions and provinces, although Ontario and Quebec account for 60% of all sales [120].

This industry has increasingly adopted SM technologies to remain competitive and increase productivity. It has leveraged SM to improve productivity, quality control, and traceability [121]. Some of the specific SM technologies widely in use across the food and beverage manufacturing sector in Canada include augmented reality, AI, ML, and data analytics. More than 50% of food industry recalls are caused by errors in processing; this can harm customers and reduce profits. To reduce errors, manufacturers are using augmented reality technologies that enhance worker health and safety and help companies comply with the personnel and sanitation regulations essential for food safety [121]. AI, ML, and data analytics are also being employed to support predictive maintenance goals. In some factories, machines with intelligent sensors track their own performance and detect potential or emerging issues before they become problems. These machines send notifications to technicians when maintenance is required, enabling them to take preventive actions and fix equipment before it fails, thus reducing downtime and enhancing productivity [122].

3.6.3 Relevant Initiatives, Funding, and Support

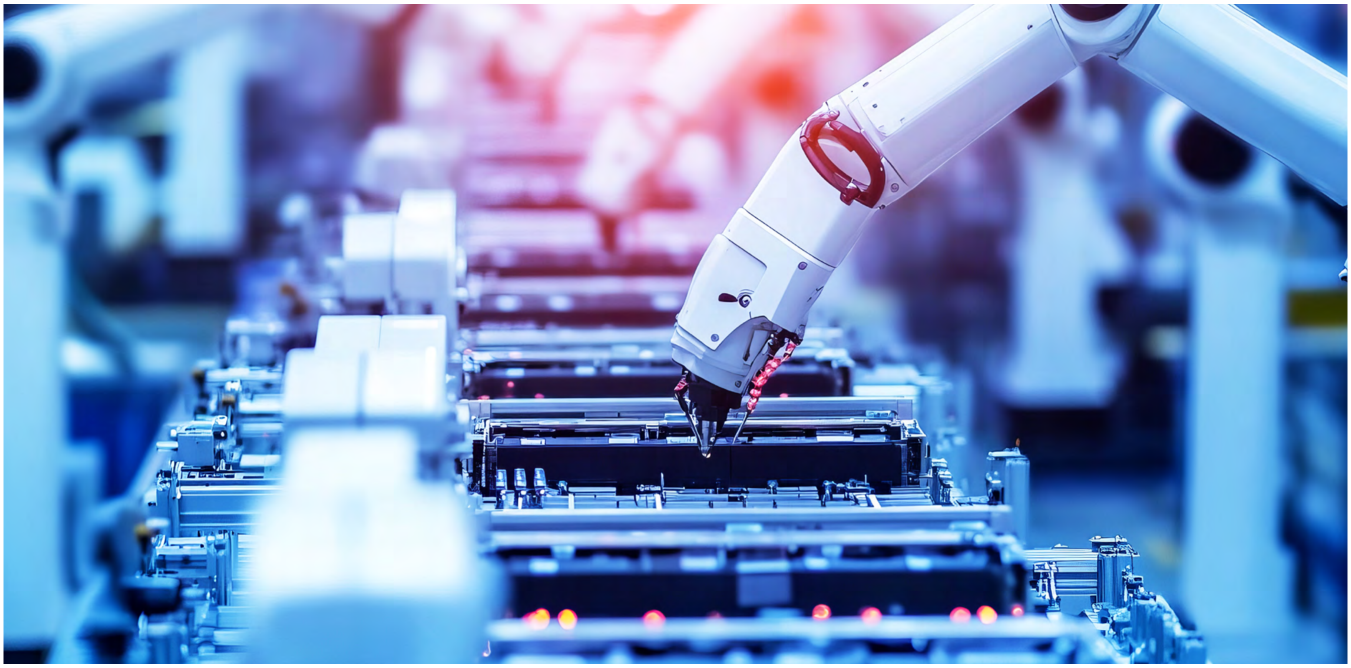
3.6.3.1 Canadian Policy Initiatives

In Canada, the development of the SM sector has been supported and enabled by a series of policy initiatives, primarily at the federal level. The efficacy of policy is important to the sector as it signals national priorities and induces interest and investment from both national and international SM stakeholders. Unlike other leading international jurisdictions, Canada's federal government has not yet authored an SM strategy, although strategic efforts have been launched, including the Economic Strategy Table for Advanced Manufacturing [123]. This strategy table is one of seven launched by Innovation, Science and Economic Development Canada (ISED) to advance sectors within its purview. Other tables supported in this manner are related to tourism, agri-foods, clean technology, digital industries, health/biosciences, and resources of the future [123]. The SM strategy table, launched in 2017, was a new model for industry–government collaboration at that time [123]. It was part of the federal government's Innovation and Skills Plan to support sector-based economic growth [105].

The advanced manufacturing table included representations from 12 leading Canadian manufacturers. Government was represented at the table by FedDev Ontario and the National Research Council Canada (NRC). In a September 2018 report produced by this table, global competition, skills shortages, lagging technology adoption, fluctuating commodity and dollar prices, and slowing United States growth were identified as the key challenges facing the Canadian SM sector [105]. At that time the table proposed four key initiatives: CANEXPAND (the focus to create and empower anchor firms and attract global investment); Skills and Talent Initiative (the focus to develop and launch a SM skills and talent immigration pathway); CANADVANCE (the focus to create a network of technology adoption centres to link innovators with established manufacturers and grow productivity); and the Hypergrowth Initiative (the focus to support scaling by providing support for manufacturers) [105].

3.6.3.2 SM-Related Financing and Support Initiatives

In Canada, various governments (federal and provincial), Crown corporations (created by governments), non-governmental organizations (NGOs) (often funded by governments), private sector entities, academic institutions, and partnerships of some of the above



support the development and use of new smart technologies such as those used in manufacturing. Many of these actors provide financing in the form of grants, tax credits, direct funding, and other supports and incentives to manufacturers wishing to develop, adopt, or effectively use new technologies. Some also have a mandate to incentivize and encourage greater private-sector investment in smart technologies employed in the manufacturing industry.

Given that access to financing is critical for companies wanting to adopt SM technologies—largely because it helps them to overcome initial capital costs—these financing and support initiatives tend to be widely supported. Indeed, they can help companies to de-risk the adoption of new technologies, improve their ROI, enhance their overall competitiveness, and become more resilient to market pressures.

3.6.3.3 Government Incentives, Credits, and Funding

One of Canada's marquee financing programs important to SM is the Scientific Research and Experimental Development tax incentive/credit program (SR&ED). SR&ED supports Canadian businesses to conduct R&D [125], and it is one of Canada's most utilized tax credit programs [126]. Indeed, it is the largest single source of federal government support for business-led R&D, providing more than C$3 billion in tax incentives to over 20,000 claimants annually [126]. For many Canadian SMEs interested in SM, the SR&ED program is the first port of call when seeking financing. The large number of innovations and early-stage technologies produced in Canada each year is a testament to SR&ED's usefulness. Given that many such technologies are new and untested, the program is particularly important because it creates essential SM test environments that allow companies to experiment and trial emerging technologies. In the 2024 Fall Economic Statement, the government surpassed its Budget 2024 commitment by proposing a C$1.9 billion investment over six years, along with significant reforms to the SR&ED program [126].

SR&ED is not the only federal program of interest to those wishing to develop and/or adopt SM-related technologies in Canada. In 2018, the federal government created the Accelerate Investment Incentive (AII) program [127]. This initiative allows companies to write off large shares of the costs of newly acquired capital assets, such as manufacturing equipment. It also allows businesses to immediately write off the full cost of specified clean energy equipment. The AII mirrors similar successful programs used in the EU and the United States. It has been well received by Canadian industry actors, including those involved with SM.

Another federal program of interest to manufacturers in Canada is the Strategic Innovation Fund (SIF) administered through ISED [128]. This program provides funding for activities related to R&D, commercialization, business expansion, investment attraction, and technology development and demonstration.

Notwithstanding the proliferation of government financing and support programs across Canada of relevance to SM, there remain significant opportunities to further support the development of SM. For instance, the SR&ED program presents a valuable opportunity for Canadian companies, especially SMEs, to access government technology funding. By refining the funding eligibility criteria and simplifying the application process, it can potentially encourage more SM-related applications. Enhancing support for companies with limited internal capacity will help them navigate the funding environment more effectively. Addressing issues related to fund stacking, eligibility, and disbursement delays will further streamline these processes, making the program even more beneficial for all participants.

3.6.3.4 Non-Governmental Funding and Support

The federal government also supports SM in Canada by providing funding to external intermediary organizations, including Crown corporations and select industry-led non-governmental organizations, which in turn support the industry. For instance, in February 2023, the federal government created a new Crown corporation, the Canada Innovation Corporation (CIC), with a budget of C$2.6 billion over four years [129]. The CIC is tasked with enhancing national innovation capacity related to its strategic priorities, which align well with SM sector growth goals: the creation of a platform for program experimentation; provision of support for strategic procurement; and the attraction of highly skilled talent to Canada [129]. According to the statement released by the Department of Finance Canada and ISED on December 19, 2023, the full implementation of the CIC is scheduled to be completed by 2026–2027 [130].

One high-profile example of an industry-led NGO that is engaged in advancing the development and growth of SM in Canada is NGen, the not-for profit administering Canada's Global Innovation Cluster for Advanced Manufacturing [111]. Funded by the Government of Canada, NGen is one of five national networks, or clusters, supported by Canada's Global Innovation Cluster (Note: In 2022, an additional C$750 million was earmarked for five more years) [131]. NGen is focused on building next-generation manufacturing capabilities by encouraging industrial digitalization, maximizing competitiveness, and increasing Canada's participation in global markets. As of 2022, NGen had approved over 167 advanced and SM projects with a total value of C$605 million [132]. According to NGen's 2023 annual report, the GDP impact from these investments over 10 years is thought to be more that C$13.5 billion [133]. Projects will also likely create more than 13,500 jobs [133]. According to its 2023–2024 annual report, NGen's project portfolio, as of the end of March 2024, included 210 projects with C$291.8 million invested. NGen funding is expected to attract an extra C$443.7 million from industry contributions, resulting in a total project investment of C$658.5 million [134].

3.6.3.5 SM-Related Partnership Initiatives

Strategic multi-stakeholder partnership initiatives, including clusters, networks, and alliances, have played, and continue to play, an important role in the development and adoption of SM technologies across Canada. Such collaborative arrangements, which are often led, facilitated, or brokered by post-secondary institutions or industry-focused NGOs, are particularly valuable when it comes to applied research, mentoring, training, capacity building, and attracting and retaining the skilled workers needed for sector growth. Many examples of universities, research institutes, manufacturers, investors, technology developers, governments, and customers working together to strengthen the sector can be found across the Canadian SM ecosystem.

For instance, the Canadian Manufacturers & Exporters (CME)—an industry-focused non-profit entity that often acts as a "collaboration broker"—has worked for years with various SM stakeholders across Canada, including universities, economic development agencies, technology developers, manufacturers, and government agencies, to develop and implement initiatives that help manufacturers adopt Industry 4.0 technologies. For example, in 2022 with the support of NGen, CME launched the Advanced Manufacturing Cluster: Newfoundland and Labrador, an initiative that now regularly brings together key stakeholders interested in working to grow the SM sector in that province [135]. In 2022, CME also worked closely with the Prairies Canada Economic Development Agency and other stakeholders to launch a Manufacturing Accelerator Program in Manitoba [136].

An example of collaboration specifically focused on talent development in Canada is the multidisciplinary learning network at the Toronto Institute of Advanced Manufacturing (TIAM). TIAM supports applied research/learning activities that encourage the sharing of knowledge and resources among SM stakeholders. Through training and education, the network translates lab-based technologies into commercial and scalable ones that can advance the sector [137]. Other examples of talent-focused collaboration are the University of Toronto's Factory of the Future, which aims to transform SM by preparing leaders to develop new robotics, automation, smart sensing, and human–machine collaboration products and systems [137], and Concordia University's Centre for Advanced Manufacturing, which brings together expertise from manufacturing, materials science, and engineering to conduct research, train engineers, and assist companies to improve existing and develop new Industry 4.0 technologies [138].

3.7 Standards and SM in Canada and Abroad

In recent years, standards development activities related specifically to the field of SM have become prolific [139]. DIN alone had 33,500 documents in its German standards collection as of 2024 [140], and 688 of them are directly related to Industry 4.0 [141]. Many more are under development today via various large international SDOs. In addition, there are also many manufacturing standards not directly focused on SM systems, but that carry some relevance for the ecosystem. In this report, we present selected examples that demonstrate the types and range of standards available to support SM.

Some of the standards presented are unique stand-alone standards that address a key issue or technology of importance to those working in the SM arena. Others are sub-standards of direct relevance to SM that are part of a broader or more comprehensive series of standards that are also relevant to traditional manufacturing. Still others are not specifically intended to address SM but are indirectly relevant to those in the SM sector. Overall, these examples focus on varied areas of importance to SM: interoperability and connectivity; data management and analytics; cybersecurity; automation and control; human–machine interaction and robotics; additive manufacturing; AI, ML, and Big Data; supply chain management; and sustainability and resource efficiency. In addition, several general and cross-cutting standards of relevance to SM (i.e., they are relevant regardless of issue or technology) are also discussed. Finally, although it can be argued that all of these standards can potentially contribute to the advancement of SM in Canada, some may be more relevant and essential to some SM enterprises than others.

Standards might play a crucial role in the SM sector by potentially enabling communication and innovation across manufacturing systems, processes, and jurisdictions. They could be vital in facilitating interoperability and integration of various devices, data, services, and systems throughout the manufacturing lifecycle. Additionally, standards might help reduce uncertainty related to new technology adoption and development by providing guidelines and examples of leading practices. These practices could enhance efficiency, productivity, quality, innovation, and competitiveness within and across the entire manufacturing ecosystem [142].

Twenty-three SM-related standards (or series of standards), organized into 10 categories, are described below in Table 2. While not comprehensive, this group or cluster of standards can serve as an SM standards starting point or primer for those interested in learning more about standards considered relevant to SM in Canada.

Table 2: Examples of Standards Considered Relevant to SM

Category	Name	Details	For more information
Interoperability and Connectivity	***ISO 23704-1-3:2022*** *– General requirements for cyber-physically controlled smart machine tool systems (CPSMT) (Part 1: Overview and fundamental principles; Part 2: Reference architecture of CPSMT for subtractive manufacturing; Part 3: Reference architecture of CPSMT for additive manufacturing)*	CPSMT systems are indispensable to SM because they help to make manufacturing processes and systems more efficient, cost-effective, accurate, and flexible; they also lead to cheaper and higher quality products overall. Part 1 of this three-part standard specifies the concept of and fundamental principles underpinning a CPSMT system; Part 2 presents a reference architecture for a CPSMT system related to subtractive manufacturing; and Part 3 presents a reference architecture for a CPSMT system related to additive manufacturing.	www.iso.org/standard/76731.html www.iso.org/obp/ui/en/#iso:std:iso:23704:-2:ed-1:v1:en www.iso.org/obp/ui/en/#iso:std:iso:23704:-3:ed-1:v1:en
	ISO 11354-1:2011 & ISO 11354-2:2015 *– Advanced automation technologies and applications: Requirements for establishing manufacturing enterprise process interoperability*	Enterprise interoperability is fundamental to SM; it is widely recognized that enterprises that interoperate across the lifecycle of a product can reduce costs and shorten delays. Part 1 (framework for enterprise interoperability) of this standard identifies and addresses three categories of interoperability barriers: conceptual, technological, and organizational and Part 2 (maturity model for assessing enterprise interoperability) specifies measures for assessing the capability of a specific enterprise to interoperate with another. It also describes a method for identifying where enhanced capabilities are required to achieve a high degree of interoperability.	www.iso.org/standard/50417.html www.iso.org/standard/57019.html
	ANSI/ISA-95 *– Enterprise-control system integration (IEC/ISO 62264-1:2013*	This standard includes models/terminology that can be used to help users determine the information that needs to be exchanged between systems. It can be used as a guide for defining user requirements, picking suppliers, or developing systems/databases.	www.sw.siemens.com/en-US/technology/isa-95-framework-layers/ www.iso.org/standard/57308.html
Data Management and Analytics	***ISO/IEC 30141:2018*** *– Internet of Things (IoT) Reference Architecture* ***ISO/IEC 30141:2024*** *– Internet of Things (IoT) Reference Architecture*	This document provides a standardized reference architecture using common vocabulary, reusable designs, and best practices. It presents a conceptual model as a basis from which to develop context-specific architectures and systems. It is to be replaced by ISO/IEC DIS 30141.	www.iso.org/standard/65695.html www.iso.org/standard/88800.html
	IEEE 2671-2022 *– Standard for General Requirements of Online Detection Based on Machine Vision in Intelligent Manufacturing*	This document outlines guidelines to implement machine vision systems; specifies requirements for data format, quality, and transmission processes; and provides descriptive application scenarios and performance metrics.	https://aistandardshub.org/ai-standards/standard-for-general-requirements-of-online-detection-based-on-machine-vision-in-intelligent-manufacturing/
	ANSI/MTC1.4-2018 *– MTConnect Standard*	This document defines data models that clarify how information relates to manufacturing. These models can be used to enhance data acquisition capabilities, expand the use of data-driven decision making in operations, and enable software applications and equipment to move towards plug-and-play environments. The models also aim to reduce the cost of software system integration.	https://static1.squarespace.com/static/54011775e4b0bc1fe0fb8494/t/5c1a7a18c-2241b6a02f43853/1545239070001/ANSI_MTC1_4-2018.pdf

Category	Name	Details	For more information
Cybersecurity	***ISO/IEC 27000:2018 & ISO/IEC 27001:2022*** *– Information security, cybersecurity and privacy protection – Information security management systems (Requirements)*	This is standard for information security management systems (ISMS). It offers guidance regarding establishing, implementing, maintaining, and improving an ISMS. It builds on other standards in the ISO/IEC 27000 series.	www.iso.org/standard/27001 www.iso.org/standard/73906.html
	ISA/IEC 62443 *– Security of Industrial Automation and Control Systems*	This is a series of nine base standards that address cybersecurity for operational technology in automation and control systems. The standards apply to a wide range of industries and technical areas. They help manufacturers adopt security as part of their operations lifecycles and better ensure compliance across their supply chains.	https://21577316.fs1.hubspotusercontent-na1.net/hubfs/21577316/2023%20ISA%20Website%20Redesigns/ISAGCA/PDFs/ISAGCA%20Quick%20Start%20Guide%20FINAL.pdf www.isa.org/standards-and-publications/isa-standards/isa-iec-62443-series-of-standards www.mom-institute.org/wp-content/uploads/2021/06/Leaflet-MS021-Cybersecurity-for-Manufacturing-ISA-IEC-62443.pdf
Automation and Control	***ISO 23247:2021 –*** *Automation Systems and Integration – Digital Twin Framework for Manufacturing*	This series defines a framework to support the creation of digital twins of manufacturing elements, including personnel, equipment, materials, and processes. Its four parts discuss general principles, requirements for developing digital twins, reference architecture with functional views, and technical requirements for information exchange between entities within reference architectures.	www.iso.org/standard/75066.html
	ISO 16400-1:2020, 16400-2:2024, 16400-3:2024 *– Automation systems and integration – Equipment behaviour catalogues for virtual production system*	This standard introduces equipment behaviour catalogues that offer standardized ways for providers to communicate equipment behaviours. It describes requirements for creating executable models that represent dynamic behaviours (important when configuring virtual production systems) and describes requirements for building equipment instance models.	www.iso.org/standard/73384.html www.iso.org/standard/76812.html www.iso.org/standard/76813.html
	ISA88 *– Batch Control*	This document provides guidelines for the specification/design of batch control systems as used in process control industries. It defines terminology that serves to encourage understanding between manufacturers and users; presents a standard data structure language that simplifies programming, configuration tasks, and communication between various components of a system; and provides a data structure for batch systems that simplifies communications within the system.	www.isa.org/standards-and-publications/isa-standards/isa-standards-committees/isa88

Category	Name	Details	For more information
Human-machine Interaction and Robotics	***ISO 9241-210:2019*** *– Ergonomics of human-system interaction – Part 210: Human-centred design for interactive systems*	This document helps managers of hardware and software design and re-design processes to identify/plan effective and timely human-centred design activities. It includes requirements and recommendations for human-centred design, including principles and activities that can be used across the lifecycle of a computer-based interactive system; addresses technical human factors and ergonomics issues to help users understand their relevance/importance in design processes; and includes an overview of the complete multi-part ISO9241 series and a checklist for assessing standard conformance.	www.iso.org/standard/77520.html
	ISO 10218-1-2:2011 *– Robots and robotic devices – Safety requirements for industrial robots (Part 1: Robots); Robots and robotic devices – Safety requirements for industrial robots (Part 2: Robot systems and integration)*	Part 1 specifies the requirements and guidelines for the inherent safe design of and protective measures and information needed for using industrial robots. It describes the basic hazards associated with robots and provides requirements to eliminate or reduce risks associated with them. Part 2 describes the basic hazards and hazardous situations identified with robotics systems and provides requirements to eliminate or adequately reduce the risks associated with those hazards. It also specifies requirements for the industrial robot system as part of an integrated manufacturing system.	www.iso.org/standard/51330.html www.iso.org/standard/41571.html
Additive Manufacturing	***ISO/ASTM 52900:2021*** *– Additive manufacturing – General principles – Fundamentals and vocabulary (Edition 2)*	This document provides a basic understanding of the fundamental principles for additive manufacturing processes; gives clear definitions for terms and nomenclature associated with additive manufacturing technology; and aims to facilitate communication between people involved in this field of technology.	www.iso.org/standard/74514.html https://xcelerator.siemens.com/global/en/all-offerings/solutions/s/smart-additive-manufacturing.html
	ISO/ASTM 52910:2018 *– Additive manufacturing – Design – Requirements, guidelines and recommendations*	This document includes the requirements, guidelines, and recommendations for using additive manufacturing in product design. It is applicable for all types of products, devices, systems, components, or parts that are fabricated. It helps determine which design considerations can be best used in an additive manufacturing project and provides general guidance and identifies issues that can emerge. It is intended for those designing products to be fabricated, students who are learning mechanical design and computer-aided design, and developers of design guidelines and guidance systems for additive manufacturing.	www.iso.org/standard/67289.html?browse=tc

Category	Name	Details	For more information
AI, ML, and Big Data	***ISO/IEC 23053:2022*** *– Framework for Artificial Intelligence (AI) Systems Using Machine Learning (ML)*	This document presents a common terminology and set of concepts for AI and ML systems, as well as a framework for the description of AI systems that use ML. It discusses various considerations that apply to the engineering and use of AI systems, including system components and their functions in an AI ecosystem. It addresses deep learning as an ML method, and it is applicable to all types/sizes of entities that are implementing AI.	www.iso.org/standard/74438.html
	ISO/IEC 42001:2023 *– Information technology – Artificial intelligence – Management system*	This document specifies the requirements for establishing, implementing, maintaining, and continually improving an Artificial Intelligence Management System. It provides guidance for those working within this rapidly changing field, including those in the SM sector; addresses many challenges posed by AI related to ethics, transparency, and continuous learning; presents a structured way to manage AI risks and opportunities; and is compatible with other quality, safety, security, and privacy management systems.	www.iso.org/standard/81230.html
	ISO/IEC 20546:2019 *– Information technology – Big Data – Overview and vocabulary*	This document provides a set of terms and definitions that promote improved communication/understanding of this area. It provides a conceptual overview of the field and its relationship to other technical areas and related standards; provides an overview of key concepts from the broader computing domain that are cross-cutting with respect to Big Data; aims to provide users with information about the data and processing characteristics of Big Data; and discusses issues related to dataset analysis, business considerations, and cost-effectiveness as it relates to the use of Big Data.	www.iso.org/standard/68305.html
Sustainability and Resource Efficiency	***ISO 20140-1:2019*** *– Automation systems and integration – Evaluating energy efficiency and other factors of manufacturing systems that influence the environment – Part 1: Overview and general principles*	This document aims to contribute to enhanced environmental performance by helping users evaluate the specific performance and impacts of systems. It provides an overview and describes general principles of environmental performance and presents a method for evaluating performance regarding energy consumption and waste. It applies to discrete, batch, and continuous systems or to parts of such systems, and it can be used to benchmark performance against a generic system reference or for comparing systems. It can also be used to set targets and monitor operations.	www.iso.org/standard/69358.html
	ISO 14052:2017 *– Environmental management – Material flow cost accounting – Guidance for practical implementation in a supply chain*	This document guides the implementation of material flow cost accounting (MFCA) in a supply chain. It includes scenarios for improving material and energy efficiency, principles for successful application of MFCA, and practical steps for implementation. It applies to any entity that uses materials and energy, regardless of its products, services, size, structure, location, or existing systems. When applied as an accounting tool across a supply chain, economic and environmental benefits, such as reduced material and energy losses and increased collaboration and trust among supply chain entities, can be realized.	www.iso.org/standard/54811.html#:~:text=ISO%2014052%3A2017%20provides%20guidance,MFCA)%20in%20a%20supply%20chain

Category	Name	Details	For more information
Supply Chain Management	***ISO 28000:2022*** *– Security and resilience – Security management systems – Requirements*	This document specifies the requirements for a security management system, including aspects critical to supply chain security. It can help a user assess the security environment in which it operates, including its supply chain dependencies and interdependencies. It can help them to determine the adequacy of existing security measures and manage their compliance with statutory, regulatory, and voluntary obligations. It offers users a Plan-Do-Check-Act planning model that can be used to implement, operate, monitor, review, maintain, and continually improve organizational security. It is relevant to the SM sector because its dynamic and evolving nature exposes it to uncertainty and volatility in its security environment.	www.iso.org/standard/79612.html
	ISO/IEC 17360:2023 *– Automatic identification and data capture techniques – Supply chain applications of RFID – Product tagging, product packaging, transport units, returnable transport units and returnable packaging items*	This document defines the basic features for use of radio-frequency Identification (RFID) technology in supply chain processes; provides specs for item identification; makes recommendations about information to include on RF tags; provides information on semantics and data syntax to be used; and discusses data protocols needed so business applications and an RFID systems can interface effectively. It also helps users develop a consistent/reliable means of identifying and tracking items that in turn can result in improved traceability and information transparency, reduced errors, improved inventory management, and increased customer satisfaction.	www.iso.org/standard/83586.html www.iec.ch/blog/five-ways-isoiec-17360-enhances-supply-chain-efficiency
General and Cross-Cutting Standard of Relevance to SM	***ISO/IEC TR 63306-1:2020*** *– Smart manufacturing standards map (SM2) – Part 1: Framework*	This document was developed to provide a credible, central, and neutral repository of information about standards related to SM. It includes a framework/vocabulary to be used for developing entries for the Smart Manufacturing Standards Map Catalogue and enables mapping and linking of SM standards. It includes visualization tools useful for sorting, classifying, and comparing standards and that help SDOs identify standards that apply to their respective domains and generate comparisons between the relative positioning of different standards. Tools also help users identify relevant standards for their activities, evaluate their activities in terms of relevant standards, and build product development roadmaps in accordance with the standards landscape.	www.iso.org/standard/81277.html

When different architectures, data exchange formats, semantics, interfaces, and technologies are involved in manufacturing, as is the case with SM, it is critical to have up-to-date and relevant standards that can effectively advance communication, integration, and interoperability. In keeping with this essential need, numerous high-profile international and national standards organizations including ISO, IEC, Institute of Electrical and Electronics Engineers (IEEE), Industrial Internet Consortium, NIST, and DIN, as well as consortia and collaborative efforts initiated by them, are regularly developing and refining standards. The exact number of SM standards available at any given time in this dynamic standards environment is difficult to ascertain. Not only are SM-relevant standards created and maintained at multiple scales by numerous organizations working at various levels (i.e., internationally, regionally, nationally, and by sector), but they also cover a range of diverse industrial processes and practices (e.g., strategy, workforce, supply chain) [139, 142, 143].

Moreover, they reflect varied lifecycle dimensions (e.g., product, production system, business) and address a wide range of technologies and related areas important to those in the SM sector, such as cybersecurity. Notwithstanding the impressive work being undertaken to develop and improve standards, and perhaps not surprising given the speed at which the SM sector is growing and evolving, a number of needs, gaps, and challenges relevant to SM standards are emerging. Some of the needs, gaps, or challenges identified through this project via its literature review and interviews can be considered high-level and/or cross-cutting. On the other hand, some challenges, gaps, or needs are specific to individual standards, such as the perceived high cost of adoption for certain companies.

4 Integrated Analysis and Recommendations

4.1 Canada Compared to Leading SM Jurisdictions

There are some key similarities and differences between the Canadian manufacturing sector and those found in the leading jurisdictions of the United States, Germany, and Singapore (see Table 3).

Some important observations about SM and practices of direct relevance to Canada can be gleaned from a review of these jurisdictional similarities and differences:

Table 3: Comparing Canada with the United States, Germany, and Singapore on Key Benchmarks

SM Solutions	United States	Germany	Singapore	Canada
Manufacturing value added: % of GDP [81] *(Rounded percentages to the nearest percent)*	10% (2020) 11% (2021)	19% (2020) 19% (2021 & 2023)	20% (2020 & 2021)	9% (2020)[1]
Presence of national SM strategy	Partially (National Strategy for AM) [71]	Yes (Industrie 4.0) [84]	Yes (Manufacturing 2030 Vision) [98]	No
Role of government in SM governance	Preference for private-sector leadership [67]	Active role for government [67]	Active role for government [98]	Active but preference for private-sector leadership [98]
2020 R&D spending: % of GDP [144]	3.47%	3.13%	2.21%	1.89%

[1] Latest data available [81]

1. **Manufacturing Value Added:** Germany and Singapore have a higher percentage of their GDP coming from manufacturing (19% and 18% respectively) compared to the United States (11%) and Canada (9%). This indicates a stronger reliance on manufacturing in their economies.
2. **National SM Strategy:** Germany and Singapore have comprehensive national SM strategies (Industrie 4.0 and Manufacturing 2030 Vision, respectively), while the United States has a partial strategy focused on advanced manufacturing. Canada lacks a dedicated national SM strategy, which could impact its ability to coordinate and advance SM initiatives effectively.
3. **Government Role in SM Governance:** Germany and Singapore have governments that play an active role in SM governance, which can drive coordinated efforts and support for SM initiatives. In contrast, the United States and Canada prefer private-sector leadership, although Canada's government is somewhat active in this area.
4. **R&D Spending:** The United States leads in R&D spending as a percentage of GDP (3.47%), followed by Germany (3.13%), Singapore (2.21%), and Canada (1.89%). Higher R&D investment is crucial for innovation and advancement in SM technologies.

Canadian SM stakeholders can look to Germany and Singapore for ideas about how to advance SM. For instance, from Germany, SM leaders could learn about the importance of cross-sector collaboration, with an emphasis on the need for a broad national public–private SM strategy. Canada can also gain insights about how to improve its sector by examining the innovative ways in which the German government financially supports its SM sector. Singapore's approach to supporting SM can also serve as a leading practice example for public–private co-operation in Canada. While Singapore's government is responsible for the sector's overarching vision/strategy, it is also expected that private-sector actors will co-operate effectively on SM matters. In Singapore, multiple ministries work together to support the SM sector. Substantial amounts of public funding are made available to both SMEs and large companies so they can implement innovative technologies into their workflows. Government also invests heavily in SM via tax credits, human capital development, and other incentives.

As Canada aims to strengthen its position in the SM landscape, focusing on strategic areas for development, drawn from leading SM jurisdictions, such as the United States, Germany, and Singapore, could help enhance its competitiveness and foster innovation. Below are some of the identified areas to be considered:

- **Strong Government Support:** This support could help to create better conditions for SM through government–industry partnerships, increased R&D funding, and supportive policies. Due to government backing and partnerships with industry, the United States, Germany, and Singapore have all been successful in developing robust SM infrastructures. Canada's governments could also create better conditions for SM by supporting partnerships, increasing R&D funding, and establishing supportive policies.
- **Skill Development and Workforce Transformation:** It is important to establish workforce upskilling programs and invest in educational institutions to prepare Canadian workers for Industry 4.0 opportunities.
- **Collaboration and Ecosystem Development:** Canada could better foster the collaborative ecosystems that bring together manufacturers, technology providers, and academic institutions, and that could drive innovation and knowledge development related to Industry 4.0, such as Germany's Industrie 4.0 initiative, which supports collaboration.
- **Focus on SMEs:** Following the examples of the United States, Germany, and Singapore, Canada could increase the number and scope of support schemes that aim to incentivize technology adoption among SMEs given that over 95% of businesses in Canada are SMEs.
- **Cybersecurity and Data Privacy:** Canadian SM entities could be encouraged/supported to seek out and develop partnerships with benchmark countries to build Canada's capability to develop robust cybersecurity and data protection measures relevant to the sector here.

4.2 Canada's Strengths and Challenges

Although Canada's SM sector is not as mature as those in leading international jurisdictions, several national and sectoral strengths present opportunities for growth and value creation. Among Canada's assets are its highly educated population [145], forward-looking immigration policies [146], abundance of natural resources [147], and access to global markets through various comprehensive free trade agreements, such as the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP) [148].

As of 2024, Canada does not have an overarching SM strategy similar to those developed for Germany or Singapore, despite Canada's industry-led Advanced Manufacturing Economic Strategy Table, which is supported by the Government of Canada via ISED, calling for one since 2018. Table members, as well as many other SM industry players, believe that such a strategy could increase Canada's competitiveness through better access to capital, talent, and markets [105].

Notwithstanding this need, the Canadian government has been actively supporting the development of the smart and advanced manufacturing sectors via varied initiatives. Tax incentives, research grants, the provision of supports for various types of industry partnerships, Canada's Innovation Global Innovation Cluster Initiative, and federal incentives such as SIF, are examples of Canada's support for Industry 4.0. The fact that Canada has relatively low business costs—the lowest in the G7 in 2019 [149]—and enjoys a stable political climate has also helped to contribute to the favourable environment for investment and innovation in the SM sector here.

Canada's robust and diverse manufacturing base, comprised of sectors such as automotive, aerospace, and pharmaceutical, provides a solid foundation for the adoption of SM technologies. Efforts to advance the manufacturing of electric vehicles in Canada, the use of additive manufacturing applications in mining, the launch of new robotic biomanufacturing projects related to cell and gene therapy, the world's first project to digitize steel production [150], and a fully automated food processing facility in Waterloo, Ontario, named by the UN as one of the top 10 SM applications in the world because of its contribution to achieving its sustainable development goals [151], are all examples of Canadian innovation related to SM. All of these examples demonstrate the strength of the nation's overall manufacturing base.

Despite Canada's growing manufacturing sector, and notwithstanding the nation's strengths related to enhancing the SM ecosystem here, Canada still has work to do if it wants to become a global SM leader [152]. According to the Business Development Bank of Canada, in a survey of 960 Canadian entrepreneurs conducted in 2017, only 40% of small and mid-sized manufacturers had invested in Industry 4.0 related projects, and only 3% had fully digitized their production processes [153]. More recently, results from a survey of senior manufacturing decision makers published in Canadian Manufacturing's 2023 Advanced Manufacturing Outlook show that while many respondents believed Industry 4.0 technologies are useful and needed, only 62% said that their company had a plan or roadmap for pursuing them [154]. Moreover, a 2022 NGen report indicates that many of Canada's current smart manufacturing assets and capabilities are not well-known among Canadian manufacturers [155]. It also highlights the need to strengthen connections between researchers, technology development companies, and manufacturers [155].

There are also some challenges associated with regulation and compliance as it relates to SM in Canada. For instance, the complex and rapidly evolving nature of SM can make it challenging for regulators to keep pace with regulations that can potentially address the risks associated with emergent SM systems [156]. The regulatory changes can lag behind technological advancements, and this time gap can create a disconnect between what is permissible under existing regulations and the capabilities offered by new SM solutions.

"Other specific challenges hindering SM growth in some Canadian regions include a lack of high-speed Internet, limited connectivity, and insufficient data storage and computing capacity."

Other specific challenges hindering SM growth in some Canadian regions include a lack of high-speed Internet, limited connectivity, and insufficient data storage and computing capacity. Additionally, Canadian manufacturing firms are lagging behind their international peers in the adoption of automation and advanced technologies. According to the Conference Board of Canada's 2024 Innovation Scorecard, Canada is ranked 15th out of 20 countries graded with a score of "C" in national innovation [157]. Other challenges noted in the review of literature and also raised in interviews conducted during this study include difficulty in establishing a strong value proposition for SM; the general lack of talent needed for SM; challenges associated with accessing capital for SM; SM-related intellectual property issues; the lack of a national SM strategy; and various SM technical challenges. All these issues and challenges may help to explain why Canada is often described as lagging behind other jurisdictions when it comes to realizing the benefits of SM.

4.3 Insights from Key Informants: Emerging Themes

4.3.1 Challenges Facing SM Adoption in Canada

The interviewees collectively provided extensive insights into the challenges faced by those involved with SM in Canada. While different interviewees highlighted various challenges, there was significant overlap in their observations. When synthesizing all comments, six core challenges emerged; these challenges are also frequently cited in literature related to SM. These challenges include an unclear value proposition, a talent gap, limited access to capital, technical issues, intellectual property concerns, and the absence of a national SM strategy. The challenges listed below are presented without prioritization:

Unclear Value Proposition

Some interviewees noted how the absence of a clear value proposition inhibits the willingness and ability of companies to dedicate resources toward capital-intensive SM investments. This lack of clarity on investment value was described as being present in both high- and low-production environments. When production is close to capacity, implementing new systems is often perceived as burdensome and unnecessary. When production is slow, the necessary capital to invest may not be available. Further to this, some interviewees noted that because most resources invested in technology do not usually lead to measurable business outcomes, they are especially hesitant to invest in SM.

Regarding how best to address this value proposition challenge, interviewees generally held the view that governments should play a role in de-risking technology capital-intensive investments. Several noted that a tool like Singapore's Smart Industry Readiness Index (SIRI), [158], could help Canadian companies better understand how SM can help them to achieve their business goals. A tool like the SIRI could potentially allow business owners to evaluate their SM readiness and analyze potential cost savings and productivity gains.

Finally, several interviewees noted that Canadian companies are generally risk-averse, and this can help to explain why they are often challenged to see the value inherent in SM. They compared the innovation culture in Canada to that in the United States. In their view, whereas Canada's culture leans toward consistent incremental growth, it is focused on disruption and radical innovation in the United States.

Talent Gap

Almost all particpants interviewed said something about Canada's talent gap. Some described it as a prominent barrier to SM technology adoption in this country. Many also expressed that Canada's labour force cannot keep up with the speed of technology development. Possible reasons for this included Canada's aging workforce and the fact that many new potential skilled employees are simply not interested in joining the manufacturing sector. Further to this, Canada's education system was described as one that does not expose young people to career opportunities in manufacturing to the same extent as systems in other leading jurisdictions. Interviewees believed strongly that there is an urgent need to expose young people to SM at an early age, especially given that one-third of Canada's manufacturing workforce will be retiring soon.

Simply put, they believed that more could be done in Canada to raise awareness about SM as an attractive career choice. Overall, in the view of some participants, Canada's talent shortage particularly inhibits the adoption and implementation of new smart technologies among SMEs. This is because smaller manufacturers often do not have the financial means to upskill existing workers. One interviewee cited that it costs up to C$100,000 to upskill a single worker. Overall, in the view of many intervieweess, Canada's talent gap, including the costs related to upskilling, help to explain why SM technologies are typically imported into Canada rather than developed domestically. In terms of addressing these talent challenges, several interviewees noted that Canada needs a long-term vision and strategy for upskilling that includes a skills-based immigration program.

Capital Access

Many interviewees noted that capital costs are a significant barrier to technology adoption in Canada. In their view, limited funding is available overall, and existing funding programs, such as those available via NGen and ISED, need to be strengthened and enhanced. According to these interviewees, many Canadian companies also have trouble navigating and accessing funding from existing programs. Start-ups and SMEs were mentioned as the types of companies that are facing the greatest capital access difficulties. In contrast to large corporations with deep pockets, these smaller entities often cannot adopt SM technology.

Further to this, the lack of funding for scaling and commercialization was described by some interviewees as a significant barrier to technology development in Canada. Participants voiced that most government funding programs related to innovation and development are targeted toward seed funding and R&D, with limited capital and support available for the latter stages of technology development. They also noted that, in their view, access to venture capital and private equity is better in the United States than in Canada. Notwithstanding these challenges associated with capital access, some interviewees welcomed the emergence of investment tax credit programs, especially those that are focused on or targeted toward SM equipment investments. They described SR&ED tax incentives as effective and important early-stage funding mechanisms for Canadian companies, although some others commented that the rigid program parameters associated with these mechanisms limit accessibility overall.

Technical Challenges

SM literature discusses numerous technical challenges associated with SM. Many of these challenges were also raised in the small group interviews. Challenges included scaling up SM solutions across multiple facilities or integrating them into the supply chain. Standardization of technologies, protocols, and data formats, crucial in ensuring compatibility and interoperability between different systems and devices, was also considered to be a concern. Technical challenges associated with legacy systems were also mentioned. Some described how integrating new machines from different manufacturers into older legacy systems can be a challenge, especially in Canada given that many end-users prefer to import cheap technologies from Europe. They also added that standards can help with system integration and technology harmonization.

Further to this, some interviewees noted that the adoption of SM technologies leads to an increased vulnerability to cybersecurity and data privacy threats. They expressed concern about how the interconnection of machinery, sensors, and networks increases the chances of a system being targeted by malicious actors. They described how many manufacturing facilities in Canada still operate legacy systems that were not designed with modern and robust cybersecurity measures in mind. Many have outdated firmware, few security patches, and insecure communication protocols, and they are highly susceptible to cyberattacks. They further noted how the process of building effective security protocols, which can work across multiple systems, is complex, if not burdensome. Some also noted the opportunity for standardization to help with the development of such protocols and reduce vulnerability overall.

Intellectual Property

Several interviewees noted how Canadian SMEs, including those active in the SM sector, do not generally operate with a long-term view or perspective. In their view, SMEs typically operate in resource-constrained environments and are thus forced to prioritize short-term financial goals and immediate revenues linked to commercial sales. They often do not have robust intellectual property (IP) strategies in place, and this limits their ability to scale and commercialize their SM innovations and technologies. A lack of awareness of the value of IP among many SMEs also helps to explain why many of them are not pursuing the development of these assets and do not have IP systems in place. In the eyes of these interviewees, there is limited awareness among SME leaders of valuation methods and the processes through which SME leaders can obtain patents and trademarks. A longer-term, more informed perspective on the value of IP generally, and of IP systems and strategies more specifically, could lead to greater private-sector investment in early-stage companies.

Lack of a Clear National SM Strategy

Several interviewees noted how the Canadian SM industry is hindered by the lack of a national SM strategy. In their view, a national strategy would organize and synergize what they see as a fragmented manufacturing ecosystem overall. For instance, a strategy that would source and upskill talent, connect suppliers and end-users, establish real-world technology test environments, and build out and expand efficient government funding and support programs could help the SM sector make important gains. One interviewee further noted that the primary benefit of a long-term national strategy would be a consistent and stable federal manufacturing policy environment; this is currently missing in Canada. Related to this, some interviewees thought that the Canadian government manufacturing policy domain is scattered, if not volatile. They explained how the policy environment appears to be ever changing and how policies that companies work hard to adapt to can be abruptly discontinued even before the benefits associated with them can be realized.

According to these interviewees, a national strategy could also be a catalyst for more and better collaboration and engagement within and across the SM sector. Both are known to have flourished in Germany, Singapore, and the United States because of the national strategies. One interviewee specifically noted that a national SM strategy in Canada would signal the federal government’s high-level commitment to the sector. In the eyes of this participant, this signal is important because, up until now, the national commitment to the sector’s long-term growth has been perceived as weak or unclear.

4.3.2 Key Challenges and Gaps in SM Standardization in Canada

The findings of this study underscore that implementing SM standards is a multi-faceted challenge involving technological complexity, security vulnerabilities, insufficient practical guidance, interoperability issues, legacy system integration, scalability concerns, and the need for industry-specific adaptations.

- **Technological Complexity:** The advanced technological requirements of SM standards can be daunting, particularly for smaller manufacturers. Implementing complex reference architectures and integrating sophisticated technologies often require significant expertise and resources, which may not be readily available to all enterprises.
- **Security Vulnerabilities:** The interconnected nature of SM systems increases the risk of cyberattacks. Without robust security measures, these systems can be vulnerable to disruptions and breaches, which poses significant risks to operational integrity and data privacy.
- **Lack of Guidance:** Many SM standards do not provide detailed, practical implementation guidance. As such, enterprises have to develop their own approaches, which can lead to inconsistencies and inefficiencies. Clear, actionable guidelines are essential to ensure uniform and effective adoption across different environments.
- **Interoperability and Integration:** Achieving seamless interoperability between diverse systems remains a significant challenge. Incompatible data formats and communication protocols often necessitate costly custom middleware solutions. To optimize SM processes, it is crucial to ensure that different systems can effectively communicate and integrate.
- **Legacy Systems:** Many existing SM standards do not fully account for legacy systems or the wide variety of proprietary technologies currently in use. Adapting these standards to older systems can be difficult, leading to partial or incomplete implementations and suboptimal performance.
- **Scalability:** SM standards must be flexible enough to accommodate enterprises of varying sizes and technological maturity. Standards that are too rigid may be difficult for less advanced users to adopt, while those that are too general may lack the specific mechanisms needed for effective implementation. If the goal is to achieve widespread adoption, standards could be tailored to address the unique needs of different users.
- **Specificity:** There is a critical need for industry-specific standards. General standards may not address the unique requirements and challenges of specific industries, leading to gaps in implementation and effectiveness. Developing tailored standards that provide clear direction and tools for each industry can significantly enhance the adoption and impact of SM technologies.

4.3.3 Key Opportunities in SM Standardization in Canada

Challenges also present opportunities, as they highlight gaps that can be addressed. Standardization gaps were identified through key informant interviews and a review of the available literature. The insights summarized below illustrate the diverse perspectives on the perceived gaps facing SM standards in Canada today, as well as opportunities to address them.

- **Data Standardization:** Improved standardization can potentially enable the development of predictive models across SM plants, optimize facilities, and facilitate the adoption of new and more complex technologies. Currently, much of the industry's data exists in silos, and there is a reluctance to share. Standardization could potentially help overcome these challenges and promote better collaboration.
- **Communication Protocols:** It is crucial to establish effective communication among all the components of a manufacturing facility and between manufacturing sites to ensure machines and equipment can seamlessly exchange data and operate as a single unit. This step involves implementing standardized communication protocols that could facilitate reliable and efficient data transfer between devices.
- **Assessment of AI Maturity:** There is also an AI maturity standards gap. While there are some AI maturity frameworks and assessment tools, the sector would benefit from a standard that helps to assess AI capacity, understand strengths and weaknesses, compare with others, and set AI goals. Existing standards, such as ISO/IEC 42001, focus on establishing and improving AI management systems but do not address company AI maturity over time. Developing such a standard would be an important step toward advancing AI use in Canada's SM sector [159, 160].

- **Cybersecurity:** Developing robust security standards specific to SM systems can mitigate the risk of cyberattacks, ensuring that all enterprises have access to best practices for protecting operational integrity and data privacy.
- **Managing Legacy Systems:** Establishing standards that account for legacy systems and proprietary technologies can aid in adapting SM standards to older systems, ensuring more complete and optimal implementation.
- **Industry-Specific Standards:** Creating tailored standards that address the unique requirements and challenges of specific industries can close gaps in implementation and effectiveness, enhancing the overall impact of SM technologies.
- **Participation on SDOs:** SM in Canada could benefit from increased participation by Canadians on SDO committees. Much important SM standardization work occurs at the international level via SDOs. Increased participation would bring new ideas, insights, and information to Canada, strengthen the country's voice in global standards development, and ensure that Canada remains competitive in the SM landscape.

4.4 Recommendations

Transitioning to SM is challenging, even for large companies with extensive datasets, due to significant issues such as data quality and format. Before adopting SM, it is essential to establish effective communication among manufacturing facility components. For instance, ensuring that machines and equipment can communicate is perceived as the first step, with generative AI adoption coming later in the process. Manufacturers should establish basic specifications and requirements before using SM; it is crucial for quality control and maintenance to define what is "normal" in production processes. This means that before manufacturers can effectively implement SM technologies, they need to set clear standards and criteria for their production processes. By defining what is considered normal or acceptable in terms of product quality and operational performance, manufacturers can ensure that the SM systems have a baseline to work from.

Corrective actions, preventive actions, and continuous improvement should be considered essential steps for digital adoption, as these practices can help streamline processes and enhance overall efficiency. It is beneficial to develop tailored tools to help manufacturers improve processes or revenue, especially for SMEs that may lack the resources for extensive internal process studies.

Effective implementation of SM technologies requires businesses to develop strategies and capabilities that address both immediate needs and long-term advancements. This involves understanding the necessary infrastructure, skills, and processes required to adopt and sustain SM technologies successfully. Additionally, businesses should refer to guidance documents on technology adoption and business process improvement to navigate the short- to medium-term challenges effectively.

Moreover, the talent gap in the workforce that was discussed previously, stresses the need for training and upskilling programs. The absence of a unified strategy for skill development was noted, making it difficult for companies to navigate. By addressing both the technological and human resource aspects, businesses can better prepare for the integration of SM technologies.

Six core challenges were identified in this study. These challenges include an unclear value proposition, a talent gap, limited access to capital, technical issues, IP concerns, the talent gap, and the absence of a national SM strategy.

In addressing key challenges for enhancing the effectiveness and adoption of SM technologies in Canada, the following strategic recommendations emerge:

Challenge: Unclear value proposition to Canadian companies in terms of ROI and lack of clarity in the specific outcomes of adopting SM technologies

- Enhanced Canadian participation in standards development: Increasing Canadian involvement in international standards development can help ensure that standards align with Canadian competitive advantages, making it easier for local companies to adopt SM technologies.

- Create total cost and benefit of ownership analysis frameworks: Developing comprehensive frameworks to evaluate the total cost and benefits of ownership can help businesses make informed decisions about adopting SM technologies.
- Develop technology evaluation standards: Establishing clear standards for evaluating technologies can help provide a structured approach for companies to assess and compare different technology options. One example of a technology evaluation scale is the Technology Readiness Level (TRL) system [161]. It offers a guide for assessing the maturity and readiness of a particular technology project being considered for deployment. With the TRL system, each project is evaluated against the parameters for each technology level and is assigned a TRL rating based on project progress.
- Identify and promote industry-specific guidelines and practices: Promoting tailored guidelines and best practices can help industries adopt SM technologies more effectively.

Challenge: Difficulties associated with capital access for small- and medium-sized companies to invest in and operate SM solutions

- Clear and user-friendly funding guidelines: These guidelines can help enterprises navigate government funding opportunities for SM. They can help clarify eligibility criteria, application procedures and deadlines, funding amounts and eligible cost categories, evaluation criteria, and reporting requirements. Currently, the complex number of funding programs available at the federal, provincial, and regional levels in Canada can create confusion for applicants. It is often challenging for organizations that are seeking funding to understand the eligibility criteria, application processes, and specific requirements of each program. Many small companies may not even be fully aware of the funding opportunities and resources available for SM initiatives. Limited visibility can make it difficult for an organization to access the funding information it needs. Clearly, there is an urgent need to improve awareness and understanding of government support programs related to SM in Canada.
- Industry investment forums for collaboration and demonstration: Organizing forums where industry stakeholders can collaborate and demonstrate SM technologies can foster investment and innovation. Investment forums can bring together companies, investors, and financial institutions to discuss and explore investment opportunities related to SM. They can provide a platform for companies to showcase projects, find collaborators, and attract potential investors. More specifically, industry investment forums can not only help participants access funding, but they can facilitate networking and partnership development. They can help manufacturers connect with potential investors, technology providers, and research institutions. Relationships nurtured at these events can lead to resource sharing, co-investment, and partnerships. Overall, these forums can help to mitigate the financial challenges associated SM.

Challenge: Complex technical challenges related to interoperability and cybersecurity as a result of the implementation and interconnection of SM solutions

- Enhanced supplier–user collaboration: Strengthening collaboration between suppliers and users can improve the integration and implementation of SM technologies. Interaction between technology providers and end-users to develop common standards that define the protocols, formats, and interfaces for interoperability would benefit the SM sector in Canada. By working together, they can ensure that standards meet the specific needs and requirements of the manufacturing industry and facilitate seamless integration and compatibility among different systems and equipment. Suppliers and users can also collaborate on joint pilot projects and testing initiatives. By working together in real-world scenarios, they can identify interoperability challenges and validate the performance of SM solutions. End-users can also provide valuable feedback and input to technology providers regarding their interoperability needs and challenges. This information can help technology providers improve their products and solutions to better align with the requirements of end-users.
- Boosted communication protocols: Improving communication protocols can ensure seamless interaction between different systems and technologies within the manufacturing process. By adhering to common protocols, SM users can seamlessly integrate various machines, sensors, control systems, and software applications, facilitating smooth data exchange and interoperability across the manufacturing environment. Communications protocols also support scalability and flexibility, allowing the SM environment to adapt and expand. As a system evolves and new components are added, communications protocols can ensure changes occur without disruptions or incompatibilities.
- Advanced cybersecurity standards and frameworks: Developing robust cybersecurity standards could protect SM systems from potential threats and vulnerabilities. SM generates vast amounts of data, including production metrics, customer information, and supply chain details. To maintain trust with customers, suppliers, and partners, it is crucial to protect sensitive data from unauthorized access, manipulation, or theft. Robust cybersecurity measures safeguard the confidentiality, integrity, and availability of critical data. Canada's SM sector needs stronger guidelines and measures for protecting SM systems and data from cyberattacks, data breaches, theft, and misappropriation. SM enterprises need to do more to enhance system and data confidentiality, integrity, availability, and resilience. Adherence to cybersecurity standards can help companies implement comprehensive security controls, risk assessment processes, and privacy protection measures. Current standards can be leveraged to meet the needs of new technologies. For example, ISO/IEC 27001 provides a framework for entities to establish, implement, maintain, and improve their information security management processes. It may be a basis on which cybersecurity standards can be adapted for SM [162].
- Create and support standards: Supporting the creation and adoption of standards could help streamline processes and ensure consistency across the industry.

Challenge: National under-investment in intellectual property assets necessary to scale, commercialize, and realize the financial gains of SM investments

- Renewed IP management processes: Updating IP management processes can help businesses protect their innovations and leverage them effectively.
- Holistic asset valuation methods: Developing comprehensive methods for asset valuation can provide a clearer picture of the value of SM technologies and investments.
- Build awareness of the need for a national IP and innovation strategy: Unlike some other leading SM jurisdictions, Canada has not invested heavily in IP asset development. Many Canadian SM companies do not have IP systems or strategies in place, possibly because of their lack of awareness of the value of IP. Building understanding of the value of IP generally, and of IP management systems and strategies more specifically, could lead to greater private sector investment in IP. The Canadian Council of Innovators believes the SM sector needs to take IP more seriously

if Canada's economy is to harness the potential of SM [163, 164]. One possible action that could help to address this challenge would be the development of a comprehensive national SM strategy for IP and innovation that could build awareness of the importance of IP and support early-stage companies to develop their IP assets. Canada's federal government and key SM sector leaders could work together to develop such a strategy.

Challenge: A prominent and growing national talent gap associated with the highly skilled workers necessary to implement and operate SM technologies

- Employ user interface (UI) standards: UI standards can help to create consistent and intuitive user experiences, reducing the training burden for new employees and enabling quicker adaptation to SM technologies. They emphasize efficient workflows and minimize cognitive load, making it easier for talent to operate SM technologies effectively. An example is DIN EN 894-1:1997+A1:2008, which outlines ergonomic requirements for designing user-friendly and safe displays and control actuators [165].
- Accredited personnel certification programs for SM: Certification programs provide many benefits to workers and the companies that employ them, such as enhanced employability, the development of standardized skill sets, and industry recognition. SM certifications are developed and endorsed by industry associations, professional organizations, and/or certification bodies. Accredited certifications define skill standards and knowledge requirements for specific SM areas. By adhering to standards, certifications could ensure consistency in skill development efforts. An example of an accredited certification is the Certified Manufacturing Technology Sales Engineer certificate from the Society of Manufacturing Engineers. It is focused on sales engineers who specialize in manufacturing technology and equipment. It covers areas such as automation, robotics, digital manufacturing, and data analytics [166]. Another example is the Kentucky Federation for Advanced Manufacturing Education Advanced Manufacturing Technician Certification. This is a work-and-learn program that combines on-the-job training with classroom instruction. It equips learners with the skills needed to work with smart technologies [167].
- Develop and/or use robust competence frameworks for SM: In a SM context, a competence framework is a structured framework that defines the knowledge, skills, abilities, and behaviours required to perform effectively in a specific role within the SM sector. It outlines the core competencies and proficiency levels needed to excel in various job functions. Developing competence frameworks aligned with SM technologies can help define the skills and knowledge areas required for different job roles. These frameworks provide a structured approach to identify and bridge skill gaps. They also enable educational institutions and training providers to align their programs with the skills demanded by the SM industry. One example of a competence framework is the Skills Framework for the Information Age developed by the global non-profit SIFA Foundation. This widely recognized competence framework for IT (and digital) professions defines skills and competency levels across various areas, including technical, business, and interpersonal [168].
- Enhance industry–academia collaboration: Collaboration between industry and academia can help to narrow the talent gap facing SM. SDOs, industry associations, and technology providers can work with educational or research institutions to develop applied research programs, internships, and apprenticeships related to SM. Industry partners can share expertise and insights with academic institutions, and help to ensure curricula are updated with the latest advancements and industry trends. Collaboration between industry and academia can provide students with the valuable work-integrated learning opportunities they need to succeed. Through internships, co-op programs, and industry placements, they can gain practical experience, work with industry experts, and develop skills that are directly applicable to SM. Joint research efforts involving industry and academia can also drive innovation in SM. By working together, groups or committees can better identify industry challenges and opportunities, develop new technologies, and explore practical solutions to real problems. Collaboration can foster a culture of

innovation and help bridge the gap between academia and real-world applications. Although industry–academia SM-related collaboration in Canada may be somewhat underdeveloped when compared to some other leading international jurisdictions (e.g., Germany), examples are emerging here, such as the Excellence in Manufacturing Consortium. This is a collaborative network of over 36,000 manufacturers from 450 Canadian communities with partners, including universities/colleges, that helps members lower costs, access opportunities, and improve efficiencies in the day-to-day running of operations [169]. NGen serves as another example of an industry-led, non-profit organization that promotes collaboration and private–public partnerships, spearheading Canada's Global Innovation Cluster for Advanced Manufacturing. NGen has demonstrated its dedication to improving next-generation manufacturing capabilities and encouraging collaboration in advanced manufacturing and innovation by reinforcing connections between industry, academia, and research institutes in Canada [170].

Challenge: Several interviewees noted that the Canadian SM industry seems to be hindered by a perceived lack of a national SM strategy

- A national SM strategy in Canada could signal the federal government's high-level commitment to the sector; this could become a catalyst for more and better collaboration and engagement within and across the SM sector.

Addressing these areas could potentially help to advance the SM sector in Canada, leading to a more innovative, efficient, and competitive manufacturing landscape.

5 Conclusions

In conclusion, this project provides a review of the SM landscape, highlighting both the opportunities for growth and the barriers that could be addressed within the Canadian context. By examining the needs, gaps, and challenges through a combination of document searches, interviews, and analysis of the information collected, this report identifies various challenges that impact the SM sector. The challenges can be considered high-level and cross-cutting.

Six core challenges are identified in this study: an unclear value proposition, a talent gap, limited access to capital, technical issues, IP concerns, and the absence of a national SM strategy. Recommendations for addressing key challenges in enhancing the effectiveness and adoption of SM technologies in Canada are also provided.

Canadian SM stakeholders can look to Germany and Singapore for ideas about how to advance SM. For instance, from Germany, SM leaders in Canada could learn about the importance of cross-sector collaboration, with emphasis on the need for a broad national public–private SM strategy. Canada can also gain insights about how to improve its sector by examining the innovative ways in which the German government financially supports its SM sector. Singapore's approach to supporting SM can also serve as a leading practice example for public–private co-operation in Canada. While Singapore's government is responsible for the sector's overarching vision/strategy, it is also expected that private sector actors will co-operate effectively on SM matters.

In terms of standardization, the findings of this study underscore that implementing SM standards is a multi-faceted challenge, involving technological complexity, security vulnerabilities, insufficient practical guidance, interoperability issues, legacy system integration, scalability concerns, and the need for industry-specific adaptations.

Finally, achieving successful SM implementation in Canada requires a thoughtful approach that balances short-term requirements with long-term vision. To navigate this journey effectively, organizations should grasp the essential components: infrastructure, skills, and processes. By simultaneously addressing technological advancements and human resource development, businesses could proactively prepare for seamless SM integration.

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Appendix A – Interview Questions

1. **Please explain your involvement with the smart manufacturing sector.**
2. **How is smart manufacturing evolving in Canada?**
3. **How is Canada positioned in the global smart manufacturing space?**
4. **Any leading practices or learnings that can be adopted from leading countries?**
5. **Are there any federal or provincial level initiatives that are currently under play that will drive smart manufacturing adoption in Canada?**
6. **Are there important technology trends in Canada or internationally that can affect Canadian manufacturers?**
7. **What are the top challenges to smart manufacturing adoption and/or smart manufacturing technologies in Canada?**
   a. Is there any prioritization to these challenges?
   b. Can a standard-based solution address these challenges? If yes, how?
   c. If no, what else could be the potential solution (for example, guidelines, tools, industry workshop, need for further research, etc.)?
8. **What are your smart manufacturing priorities over the near and longer term?**

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.