DIGITAL TWINS IN MANUFACTURING:

Lessons from Canadian Manufacturers and Technology Providers.

TRILLIUM NETWORK FOR ADVANCED MANUFACTURING

NGen Next Generation Manufacturing Canada

Table of Contents

Acknowledgements

The authors would like to thank the participating industry partners for their cooperation and support in developing this report: Avcorp Group, CenterLine, Laval International, Arvizio, EXO Insights, Hive Virtual Plant, Siemens, IBM, and the Invest WindsorEssex VR CAVE

Foreword

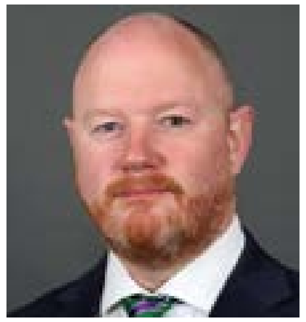
Next Generation Manufacturing Canada (NGen) is dedicated to building world-leading advanced manufacturing capabilities in Canada. The Trillium Network for Advanced Manufacturing aims to raise awareness of Ontario's advanced manufacturing ecosystem with the intention of supporting growth and competitiveness. Together, our organizations have identified some of the challenges that manufacturers across Canada face, especially as they relate to adopting new and advanced production technologies. We have also witnessed a growing number of manufacturers make important investments in such technologies as a means to improve competitiveness and achieve business objectives, and hope to share their stories.

This report builds on previous work by NGen that focuses on digital twins. It provides important terms of reference and background knowledge and presents case studies of three manufacturing companies in Canada - Laval International, CenterLine (Windsor) Limited, and Avcorp - that have recently adopted digital twins technologies. It also provides insight from a number of technology providers that support the adoption of digital twins by manufacturers.

The report aims to learn from these manufacturers and technology providers in order to educate others regarding the benefits and applications of digital twins. Our hope is that the insight gained will encourage and prepare manufacturers that hope to adopt digital twins technologies (and other advanced manufacturing technologies) in the near future.

Both of our organizations wholeheartedly agree that the future of Canadian manufacturing depends on the ability of companies to adopt these technologies. We believe that we are close to a tipping point, whereby companies that are willing to invest in advanced production technologies–technologies that are increasingly necessary to compete and achieve business objectives–will prosper, while those that lag behind will not.

NGen and the Trillium Network are but two of the non-profit organizations in Canada whose mandate is to support the growth and competitiveness of advanced manufacturing. We, along with our public and private sector partners throughout the country, will continue to collaborate on initiatives related to the development and adoption of advanced production technologies. Please do not hesitate to contact us to learn more.



Brendan Sweeney
Managing Director

Trillium Network for Advanced Manufacturing

John Laughlin
Chief Technology Officer

NGen Manufacturing Canada

Introduction

Industry 4.0 is revolutionizing manufacturing. Enabled by advances in computing power and decreased costs of data storage, the technologies associated with Industry 4.0 help integrate digital and physical production processes. The potential benefits of one of these core technologies - digital twins - have been widely lauded by those familiar with Industry 4.0, and even by those looking forward to Industry 5.0.

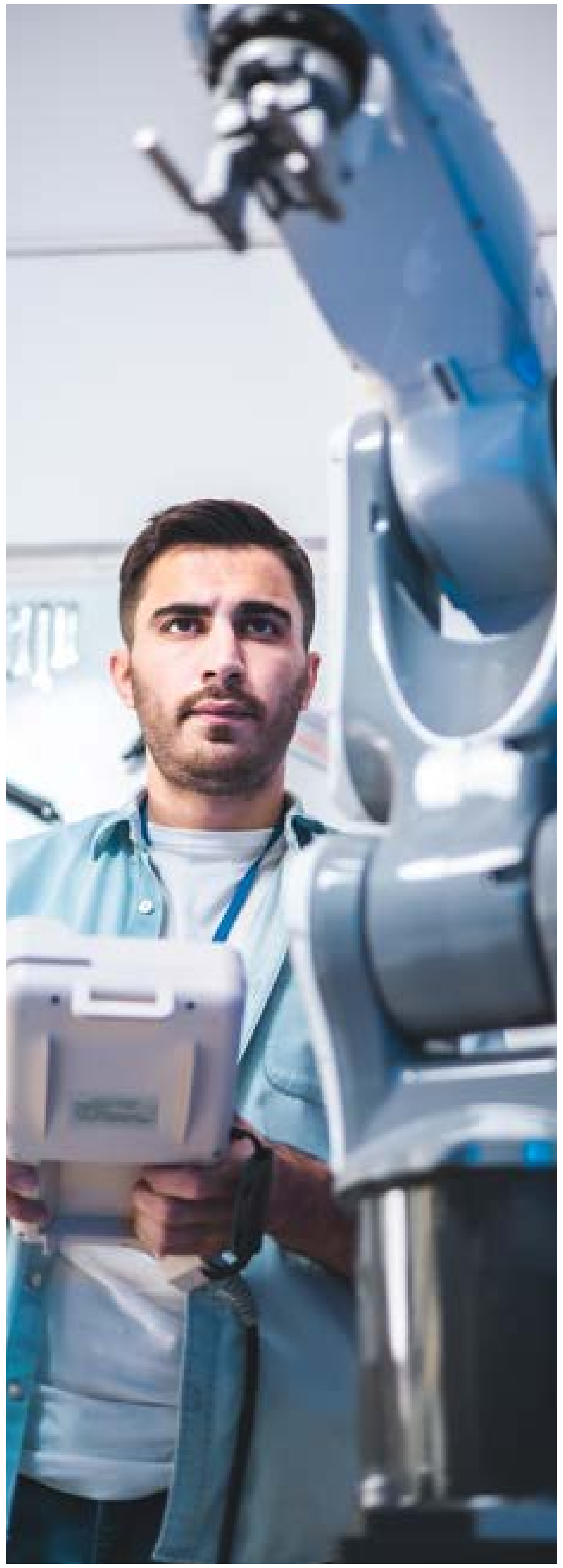
Despite these lauded benefits, small- and medium-sized manufacturers in Canada and abroad have been hesitant to integrate digital twins into their production processes. This caution is often related to high initial investment costs, a perception that digital twins are relevant primarily to the largest manufacturers, their presumed complexity, a lack of skilled personnel, and an uncertain return on investment. Moreover, this reluctance is not unique to digital twins but exists with other Industry 4.0 technologies.

In some cases, SMEs may simply not know where to start. In this report, we address these and other questions. To do so, we draw upon existing literature and research, interviews with several digital twin service and technology providers, and case studies of three Canadian manufacturing SMEs that have implemented digital twins in their production and development processes.

The remainder of the report is organized as follows.

- Section 1 defines digital twins.
- Section 2 identifies the applications and benefits of digital twins in manufacturing.
- Section 3 outlines factors that drive, enable, and create barriers to the adoption of digital twins in manufacturing.
- Section 4 presents three case studies of Canadian manufacturing SMEs that have adopted digital twins: Avcorp, CenterLine, and Laval International.
- Section 5 provides insight from service and technology providers, including Arvizio, EXO Insights, Hive Virtual Plant, Siemens Canada, and the Invest WindsorEssex VR CAVE

The report concludes with a discussion of our findings and recommendations for stakeholders seeking to facilitate the wider adoption of digital twins by manufacturers.



Digital Twins: Definition, History, Types, and Enabling Technologies

A digital twin is a realistic virtual replica of a physical object. That physical object may be a fully assembled product (e.g. a car), a part or component of that product (e.g. a wheel), a network or system (e.g. a factory), a person, or a process. The digital twin contains physical, functional, and operational information about the object that it represents. This information is used to mirror the current state or simulate the possible future states of that object.

Then-University of Michigan professor Michael Grieves first conceived of digital twins in 2002 as part of a presentation to the industry (Grieves is now the Executive Vice-President of Operations at the Florida Institute of Technology) . In 2012, the National Aeronautics and Space Administration (NASA) published a definition of digital twins within a technology roadmap to improve aviation performance . In this roadmap, they characterized digital twins as a tool that could support their goals of improving performance generally, and that could more specifically replicate conditions in space to help conduct tests for future missions . In 2014, Grieves published the first white paper focused on digital twins. His paper highlights the evolution of digital twins from a concept to their applications within and beyond aerospace . Interest in and applications of digital twins and associated technologies have increased rapidly since .

Digital twins are distinct from and more advanced than computer-aided design (CAD) and computer-aided engineering (CAE) models. What primarily differentiates digital twins from CAD and CAE technologies is their ability to continuously or periodically communicate with their physical counterparts.

A digital twin may be developed before or after the physical object is created. In both cases, the digital and physical objects must be connected in a manner that allows for the seamless exchange of data. That exchange of data may occur continuously or periodically. This connection allows the digital twin to collect data from the physical object and evolve dynamically alongside it. The digital twin can then process new information using advanced analytics, Artificial Intelligence (AI), and other simulation tools to learn more about the capabilities and limitations of the associated physical object.

The rapid increase in the interest in digital twins occurred alongside advances in other associated technologies. These include cloud computing, advanced data analytics, internet-of-things (IoT) technologies, and advances in sensor technology, all of which enable practical applications of digital twins. The development and promotion of such technologies by well-known manufacturing and technology companies such as General Electric, IBM, Siemens, Airbus, Bosch, and Rolls-Royce further accelerated the growth of digital twins .

Today, digital twins vary in complexity and in the type of physical entity they represent. Some categorize digital twins as virtual replicas of an individual component, an asset (two or more components), a system (two or more assets), or a process (two or more systems). Others focus more on two broad categories: product and process. But what fundamentally matters is that the digital twin can replicate a physical object or process - whether it is a complex product with hundreds of different parts or a process with multiple dynamic elements - and produces valuable insight and information based on that replication.

Academics have advanced the conceptual understanding of digital twins by characterizing them according to the number of dimensions involved. Three-dimensional models include a physical object, a virtual entity, and the connection between the two. Five-dimensional models include two additional elements: data and services .

The first element in both three- and five-dimensional characterizations is the physical object. The second element is the virtual entity, which requires 1) real-world measurements (e.g. size, shape, surface characteristics, material properties) and 2) geometric, physical, behavioral, and rule-based properties that replicate the physical entity and its attributes (i.e. its moving parts). To obtain the data necessary for the first aspect of the second element a digital twin relies on sensors and other cognitive technologies.

The third element in both frameworks is the connection between the physical object and the virtual entity. This refers to the networking and communications technologies and protocols that facilitate a connection between the physical and the virtual. Included here are technologies related to cybersecurity, which are vital to enabling all of the technologies related to Industry 4.0.

The fourth and fifth elements (in five-dimensional models) focus on data management tools and third-party services. Digital twins require tools to support data collection, transmission, storage, processing, aggregation, and visualization. They also require services beyond the core competencies of manufacturers that will be provided by third parties, such as cybersecurity.

Digital twins are a relatively new technology that is currently deployed by manufacturers without uniform standards. This lack of uniformity is perceived to be a limitation for more widespread use by manufacturers. To address this limitation, the International Standards Organization (ISO) is developing a new certification (ISO 23247) to guide the deployment of digital twins in manufacturing settings. This certification is currently in the approval stage and represents an important step towards the widespread adoption of a technology that is perceived by many to be a catalyst for the further development of Industry 4.0, broadly conceived.

Applications and Benefits for Manufacturing

Digital twins have several manufacturing applications. These include product design, development, testing, monitoring, fault detection, predictive maintenance, system performance, production scheduling, plant layout, training, customer experience, energy usage, and supply chain management. Digital twins are inherently reliant on collecting high-quality information, which can be used to increase efficiency and productivity, optimize processes and supply chains, and facilitate data-driven decision-making.

Product Design, Development, and Testing

Product design and development can be costly. The costs associated with developing physical prototypes can be particularly high. The ability to develop digital prototypes can lead to substantial cost-saving. The environmental and monetary costs associated with materials are also negligible when digital twins are used for developing prototypes. Furthermore, digital twins permit more experimentation with design parameters, which helps manufacturers identify optimal product configurations more cost-effectively, and can be used to simulate performance under extreme conditions that would be difficult or impossible to replicate in a laboratory setting. Finally, digital twins require input from both design and production teams in the early stages of product development, which helps erode departmental silos that cause operational efficiencies. In short, digital twins can reduce the time and costs associated with product design, development, and testing.

ElectraMeccanica , GSK , and Gastops all provide examples of how digital twins can be used in product design and development.

Real-Time Monitoring and Fault Detection

A digital twin continuously collects information about its physical counterpart with the help of sensors and other cognition technologies. These data are then used to monitor the real-time performance of products, equipment, or processes. With the help of advanced analytics and algorithms, digital twins can detect anomalies before faults occur to help address them proactively. This helps reduce the costs associated with downtime and breakdowns.

For example, STEP Tools, a New York-based company, connects machine tools to simulation servers that enable real-time analysis and corrections of machining results. According to the company, this increases the efficiency of machining processes by 15 percent through reduced tool wear and increased productivity , . The Cambridge-based Racer Machinery deploys Siemens' Sinumerik One platform similarly .

Predictive Maintenance

Digital twins use algorithms and other predictive tools to model maintenance schedules and the overall health of machinery and equipment integrated into a production line, a factory, or an entire network of factories. This approach is often found to be more cost-effective than that routine or time-based preventive maintenance, as related tasks are performed only when necessary. Moreover, certain maintenance activities may be performed remotely with the help of the digital twin. Gartner estimates that predictive maintenance using digital twins could save businesses over $1 trillion annually .

System Performance

Digital twins can help assess, predict, and optimize the manufacturing process and system performance. Advanced analytics that draws upon data from digital twins can help manufacturers detect bottlenecks and simulate alternative solutions to improve efficiency.

Dynamic and Flexible Production Scheduling

Digital twins can draw upon historical data to help schedule production in dynamic environments where flexibility is important. This can be especially useful when new constraints have been identified or when new products and processes are introduced. The impact of these changes can be tested virtually alongside production equipment. When combined with artificial intelligence technologies, digital twins can provide complete operational visibility to help factories and companies 'self-organize'. They also help to predict future resource requirements more accurately.

Plant Layout

Digital twins can virtually replicate the layout of a plant with varying levels of detail. This can allow manufacturers to test alternative layouts without having to move existing equipment or install new equipment. In addition to helping achieve production efficiencies, this can also help minimize health and safety risks.

Employee Training

Digital twins can be deployed to build immersive and interactive training experiences for employees to support upskilling or familiarization with new production equipment and technologies. In addition to training associated with regular and routine tasks, this may allow companies to provide more cost-effective training for rare but dangerous and costly emergency scenarios. Such training can be personalized for individual employees and can be conducted on-site or remotely. This type of training may be well-aligned with the learning tendencies of younger generations and persons more familiar with virtual and augmented reality technologies.

Customer Experience

Digital twins can enhance customer experience. In the automotive industry, digital twins can improve part and process tracing, leading to more efficient and effective recalls. Parts and components can be assigned a digital identity, which when combined with digital twin and blockchain technologies, allows customers to access historical information regarding damage, replacement of parts, or warranties (this may be especially useful for automotive and major appliance resale markets). In other industries, digital twins may be used to allow customers to test customized product configurations, thus providing richer and more personalized experiences.

Energy Usage

In addition to helping achieve production efficiencies and minimize health and safety risks, digital twins can be used to simulate and test processes and plant layouts that are more energy efficient. For example, Braskem, one of the world's leading producers of biopolymers, reduced energy consumption by 2.1 percent with the help of digital twins .

Supply Chains

Digital twins can be used to map out an entire supply chain. This allows manufacturers and logistics companies to monitor and simulate events that may affect the supply chain (e.g. natural disasters, trade disputes) to help identify solutions proactively. Kruger Products , one of Canada's largest integrated forest products manufacturers, recently created a digital twin of its supply chain to boost operational efficiency and flexibility.

Drivers, Enablers, and Barriers

This section reviews the work by Neto et al. (2020) [see endnote (iii)] to better understand the factors that drive, enable, and create barriers to the adoption and implementation of digital twins in manufacturing. This study was selected because of its specific focus on manufacturing and its information from manufacturers, solution providers, and consultants, as well as literature from the field. These findings are also used later to supplement the information gathered from our interviews.

Drivers

Three major external drivers motivate manufacturers to implement digital twins. The first is related to the production flexibility to satisfy market demand. Flexibility may refer to the ability to reschedule production dynamically to increase production capacity and optimize capital and resource utilization. It may also refer to the ability to develop a portfolio of products with different variants to support mass customization.

The second external driver is related to competitive forces and the need to improve cost-efficiency, quality, and productivity. This is achieved by implementing digital twins for defect identification and prevention, predictive maintenance, improvements to design and testing, and optimizing processes generally.

The third driver is related to the rate of adoption of digital twins. The more ubiquitous digital twins become, the more manufacturers will be required to invest in such technologies to keep pace.

Internal factors also drive the adoption of digital twins. First, digital twins are often implemented as part of a company- or plant-wide initiative to optimize processes, reduce costs, increase productivity, and improve product quality. Second, digital twins of products (as opposed to processes) can be deployed as part of a strategy to reduce time-to-market, enhance customer experience, or predict (and minimize) warranty claims. Third, management may see digital twins as a tool to support employee training and development and to improve health and safety outcomes. This is increasingly important during labour shortages. Fourth, manufacturers may desire to increase the transparency of processes and operations.

The value of digital twins may vary between companies and sectors. Companies that are in the best position to benefit from digital twins are:

- Those who invest extensively in physical prototypes and test their products in extreme conditions that are not possible in laboratory settings.
- Those focusing on mass production where quality issues may cause significant losses.
- Those that have incurred losses due to hazardous work environments and/or have assets spread across multiple locations and spend more on operations than on capital, lacking transparency, and incurring high unplanned maintenance costs.

Enablers

While internal and external drivers may convince manufacturers to invest in digital twins, several other factors increase the likelihood of a sufficient return on investment. These factors include existing technologies and processes, workforce competence, and organizational culture and strategy.

First, the capacity of a manufacturer to leverage capabilities related to simulation, IoT, and advanced analytics tools and software is critical to the success of any investment in digital twins. Robust cybersecurity and data storage infrastructure are also important to success. Second, a manufacturer's ability to create a well-defined implementation plan and processes to accurately correct and manage data are important enabling factors. Third, employees' familiarity with and competence related to digital technologies help successful adoption and implementation. Fourth, managers who are committed to longer-term projects and ensuring that there are adequate resources to support investments in digital twins are critical to success.

Barriers

Several factors serve as barriers to successful implementation. The lack of maturity of certain techniques and tools associated with digital twins can prevent companies from realizing the full benefits of their investments. This is especially true for more complex and advanced tools that are necessary to create predictive and autonomous responses. In the case of small and medium-sized manufacturers, a lack of familiarity with the key technologies and tools associated with digital twins poses a significant barrier to adoption. The lack of a robust and well-administered IT infrastructure can also create barriers to success.

The difficulties associated with integrating processes across multiple departments or divisions, the presence of non-standardized processes, and the absence of a clear implementation plan or roadmap can make adoption more difficult. This point may be particularly germane for multi-divisional manufacturers that treat plants as individual 'profit centers' with managers who are afforded a high degree of autonomy.

Resistance to change and skill deficiencies among staff also create barriers. The same is true for organizations with 'siloed' operations, with an aversion to risk, and with the inability to quantify the benefits or potential return on investment associated with digital twins.

Case Studies of Canadian Manufacturers

This section presents case studies of three Canadian manufacturers that have successfully implemented digital twins. The case studies are based on interviews with company personnel conducted in 2021 and supplemental publicly-available material provided by the companies.

Avcorp

The Avcorp Group designs and manufactures composite, metallic, and hybrid aerostructure components and assemblies. These are integrated into aircraft airframes (e.g. wings, fuselage). Avcorp's products are used in commercial and military aircraft developed by several of the world's largest aerospace manufacturers, including BAE Systems, Boeing, Bombardier, Lockheed Martin, and Subaru. The company employs about 550 people across three locations (Burlington, Ontario, Delta, British Columbia, and Gardena, California).

Avcorp is currently building a digital twin of one of its production lines that manufactures complex components for Boeing. The goal of this project is to develop a proof-of-concept to implement digital twins more widely across aerospace component manufacturing and to evaluate its success. Ultimately, Avcorp hopes to use digital twins to detect problems faster, predict the effect of process changes more accurately, and manufacture lighter, stronger, more durable, and more energy-efficient components. The budget for the project, which includes several partners, is $4.8 million, including a $2.1 million contribution from the Digital Technology Supercluster.

To carry out the project, Avcorp has partnered with Convergent Manufacturing Technologies, AMPD Technologies, and LlamaZOO Interactive. Each of these companies has specific expertise in either spatial planning, asset tracking, or digital process simulations. University of British Columbia students and researchers are also providing data analytics and digital twin development services.

The segment of the production line that is being replicated uses structural adhesives to bond several layers of aluminum. This bonding process eliminates the use of fasteners, reducing weight. As a high-rate process, minor improvements in efficiency lower production costs substantially. There is little tolerance, however, for quality defects. Several constraints must be addressed before adjusting the production process. A digital twin offers Avcorp an extremely useful tool to better understand the process to modify it in a manner that will generate efficiencies without compromising quality.

Avcorp has several additional motivations to adopt digital twins. First, digital twins offer an opportunity to inform managers about shop floor processes more effectively. This supports better decision-making by management. Second, creating a digital twin facilitates the digitization of other processes, such as data recording. Third, digital twins can help the company improve its understanding of flow time and capacity management.

Before building its digital twin, Avcorp improved its ability to collect data on the shop floor. This involved installing IoT sensors to automate data collection previously done on paper. However, some production equipment was not IoT compatible. In response, the company introduced new data recording and reporting processes to improve the accuracy of data gathered manually. This required a significant effort by frontline staff and managers to ensure that the new processes were being implemented properly.

Once the new data collection system was in place, the company implemented new software tools to improve simulation capabilities. This stage of the project involved developing software, much of which focused on aggregating data collected from different nodes of production. It also involved adjusting IoT sensors to improve data collection and export. While these adjustments caused some delays, they were resolved satisfactorily by Avcorp staff and other project partners.

Future phases of the project may include integrating data collection and reporting, to expedite the company's ability to make changes to production in real-time.

One of the overall objectives of the project is to evaluate the potential benefits of digital twins in all aspects of Avcorp's business. The immediate benefits are primarily related to improvements in data collection, processing, and storage. These are critical to the aerospace industry, which prioritizes product traceability. Reducing manual data collection saves time and reduces costs. This provides natural incentives for companies like Avcorp to adopt digital twins.

Another benefit is improved efficiency when changing the rate of production. Without a digital twin, Avcorp staff spend a considerable amount of time updating production plans using spreadsheets whenever a change is necessary. By running simulations through the digital twin, Avcorp's engineers can identify optimal operational changes before the change is introduced.

The company sees other potential benefits to expanding the use of digital twins. These include testing alternative plant layouts before new product launches, which happen at least once a year in each plant. The efficiencies achieved here allow staff to dedicate time to other revenue-generating tasks, which is increasingly critical during labour shortages.

The primary challenge to further adoption is related to difficulties quantifying ROI. Aerospace manufacturing involves a substantial amount of non-standardized and low-volume production. This makes estimating ROI difficult at the plant level. Another challenge is related to data privacy. Avcorp is bound by non-disclosure agreements with its customers. These agreements restrict their ability to share data with project partners and other third parties and increase the resources that the company must devote to monitoring any data-related activities.

Avcorp identified several important lessons learned through this project:

1. Define success criteria before implementing a digital twin. The best projects have robust and measurable criteria to determine success. These may include quantitative and qualitative criteria. It is important to identify these before implementation.
2. Minimize departmental silos. Building a good working relationship between IT, engineering, and production staff were critical to the project's success. Installing IoT sensors and other technological upgrades related to data collection required close collaboration between the IT department and those on the shop floor.
3. A multidisciplinary workforce is an asset. Staff with a combined knowledge of production processes and software is essential. In Avcorp's case, team members with mechatronics backgrounds were instrumental due to their knowledge of physical and digital systems.
4. Buy-in from internal stakeholders is vital. A supportive management team is essential. In Avcorp's case, this involved the support of company executives and the plant's general manager.

CenterLine (Windsor) Limited

Founded in 1957, CenterLine (Windsor) Limited is a family-owned manufacturer and integrator of automated welding and assembly lines headquartered in Windsor, Ont. The company specializes in advanced automation processes and joining technologies for resistance welding, metal forming, and cold spray applications. Its other products include welding consumables and equipment components. CenterLine (Windsor) Limited employs nearly 1,000 employees across nine manufacturing and four service support facilities in Windsor, United States, Mexico, Brazil, Germany, Romania, India, and China. About 700 of its staff are in Canada.

CenterLine (Windsor) Limited's primary customers include automotive original equipment manufacturers (OEMs) and suppliers and companies from the mass transit, aerospace and defense industries. These customers operate under significant competitive pressures. They rely on CenterLine (Windsor) Limited's automation products to reduce costs, maximize productivity, and accelerate time to market. The use of simulations and digital twins helped CenterLine (Windsor) Limited meet its customers' challenging demands.

In the past decade, two significant trends caused CenterLine (Windsor) Limited to develop its simulation and digital twins capabilities further. First, CenterLine (Windsor) Limited's customers had to adapt to shortening project timelines and expected their suppliers to follow the course. Second, while CenterLine (Windsor) Limited's customers took responsibility for most of the simulation work earlier, they gradually transferred it to their suppliers.

To adapt to these changes and remain competitive, CenterLine (Windsor) Limited had to develop its simulation and digital twin capabilities. By implementing incremental upgrades over a decade, the company gradually integrated the use of simulation and digital twins into its processes. In addition to developing its solutions, the company also invested in DELMIA digital manufacturing and simulation software from Dassault Systèmes to support this transformation.

The main application of simulations and digital twins at CenterLine (Windsor) Limited relates to designing robotic welding, manufacturing, and testing. In 2008, before adopting these techniques in its processes, a typical CenterLine (Windsor) Limited project incorporated 10 or fewer robots. The company relied on 3D design, 2D layouts, and limited simulation to execute its projects.

There were several limitations to these approaches. First, it was difficult to predict accurate cycle times for projects. Typically, as much as 85 percent of a project's duration involved processes preceding any manufacturing and integration. Delays resulting from inaccurate predictions at the early stages compressed the time needed to manufacture, integrate, and test systems. Second, visualization capabilities were limited and less sophisticated, restricting customers from understanding how the system would work once it was built. This prevented CenterLine (Windsor) Limited and its customers from accurately analyzing whether the finished robot cell would fit into customers' shop floors and processes and whether any safety issues would arise.

These limitations resulted in design deficiencies that were noticed only after a system was physically built. That translated into significant adjustments to built systems and relocating expensive and sensitive equipment around the shop floor, increasing costs and reducing customer satisfaction. With the broader adoption of simulations and digital twins since 2008, CenterLine (Windsor) Limited has overcome those difficulties. Today, CenterLine (Windsor) Limited simulates every robot, process, and piece of machinery before the robot cell production and integration begin. As a result, the company can now deliver projects that involve up to 200 robots thanks to several important advantages gained with the wider use of simulations and digital twins.

The company has reduced project timelines substantially. Large job delivery time decreased from two years to less than 50 weeks on average. Time savings were achieved in every step from design to production to delivery. For example, simulations have helped designers reach an optimal system configuration much faster in the design phase. In collaboration with production teams, potential problems are addressed earlier.

In addition, if customers ask CenterLine (Windsor) Limited to satisfy new constraints that require design alterations, updates can be made quickly. In other instances, better visualization capabilities help CenterLine (Windsor) Limited work with its customers to validate that the designs will meet their needs. Finally, CenterLine (Windsor) Limited can simulate and analyze the safety implications of its systems before delivery. That was not possible without the use of

new technologies, which helped CenterLine (Windsor) Limited avoid customer rejects based on safety concerns or costly system modifications in the late stages of projects.
In the production phase, the ability to estimate cycle times accurately (up to 90-95% accurate) allowed CenterLine (Windsor) Limited to derive efficiencies in scheduling, production planning, and project management. This has improved project budget performances and the rate of on-time deliveries. Substantial time savings were achieved by eliminating the need to rework a system once it is physically assembled. Robot teaching times have fallen by 75 percent with the use of offline programming. Moreover, because the company can now simulate entire processes before production and integration, it has moved away from being tooling-centric to process-centric. Tools are developed with the entire customer process in mind, eliminating the need to modify the system post-production. The company has achieved zero robot moves post-installation or tooling changes since the wider adoption of simulations and digital twins.

The functionality has gone beyond the design, engineering, and production stages. CenterLine (Windsor) Limited uses simulations and digital twins to provide more accurate quotes to its potential customers. Moreover, the company is more confident in its capabilities and knows what it can achieve before signing a contract. This helped CenterLine (Windsor) Limited strengthen its customer relationships.

Simulations and digital twins have helped CenterLine (Windsor) Limited generate significant business value by compressing project timelines, increasing the quality of its final products, and better meeting the needs of customers. They have helped quadruple sales by transforming CenterLine (Windsor) Limited's capabilities since 2008.

While it has been highly beneficial to the company, adopting simulations and digital twins took a long time to implement. CenterLine (Windsor) Limited's efforts spanned more than a decade. According to Allan Parks, director of engineering, "implementation is a long journey, and CenterLine (Windsor) Limited is slowly moving the chess pieces of Industry 4.0 forward." He noted the company started with 2D designs, moved on to 3D designs, and then made 3D models available to assembly personnel on the shop floor.

Only after these steps was CenterLine (Windsor) Limited able to start using simulations effectively to understand what the end product looks like. He notes that while the company is getting closer to building a full digital twin, there are still some limitations. For example, certain minor parts of the robot cells are currently not digitally replicated. The company plans to add these elements soon.

Forward-thinking management was a key asset. Understanding the potential benefits of these technologies early on, they gradually built up capabilities and invested incrementally. Educating staff about how to put these technologies in place across the entire enterprise was critical. Over time, CenterLine (Windsor) Limited's workforce gained an appreciation for these technologies.

Implementation has not been without its challenges. In the early years, specific software purchased by CenterLine (Windsor) Limited had limited compatibility and was used with existing equipment and software. This experience forced the company to look for solutions compatible with a wider range of its existing tools - it finally decided to use DELMIA. Still, some of the functionalities the CenterLine (Windsor) Limited needs are just not available off-the-shelf. Therefore, the company had to hire specialists and develop certain ancillary software internally. For example, CenterLine (Windsor) Limited engineers had to create the tools to export CAD outputs to the company's PLM system in the desired format. Initially, the company considered outsourcing some of this work, but the lack of a large pool of qualified people required it to build in-house capabilities. Today, the company employs 12 full-time staff and several contract staff across its facilities in Windsor and Romania to undertake simulation and digital twin projects.

Like some of its peers, CenterLine (Windsor) Limited also finds it difficult to calculate the ROI for these projects. Benefits are realized in many different areas, making them difficult to aggregate. However, for each incremental upgrade, investments were justified internally. Projects were approved because the management saw significant benefits from its prior total investments. While benefits are difficult to aggregate, investment-related expenses are more crystallized. Staff costs make up only a part of CenterLine (Windsor) Limited's investment. Other costs related to software licensing, servers, installing and maintaining new hardware, and training employees. The company estimates that it has invested in the range of millions of dollars in total over a decade to build up its simulation and digital twin capabilities.

Looking forward, CenterLine (Windsor) Limited will keep making incremental upgrades to its simulation and digital twin capabilities. These efforts will continue simultaneously with the company's other digital transformation and Industry 4.0 adoption projects. The company plans to incorporate additional parts and components in its virtual replicas for digital twins in the near term. Moreover, the company considers using digital twins for monitoring and optimizing its production equipment (e.g. CNC machining centers). To facilitate that shift, the company makes sure the new machines it invests in are compatible with its existing hardware and software. CenterLine (Windsor) Limited recognizes such investments are essential to remaining competitive. As Parks notes, "customers expect it, and if you do not get ahead of competitors, you will start struggling to catch up."

CenterLine (Windsor) Limited learned several vital lessons:

1. Start small and make incremental upgrades. Adopting Industry 4.0 technologies is better facilitated by having a long-term strategy and following a step-by-step approach. Implementing multiple projects at once is not practical. Managers need time to train themselves and staff for each new upgrade. In CenterLine (Windsor) Limited's case, the necessity to justify each upgrade also helped the company review its objectives, set attainable goals, and learn from each step in the process.

2. Pay attention to the limitations of off-the-shelf solutions. Off-the-shelf solutions can be limited and/or incompatible with existing systems. CenterLine (Windsor) Limited needed to invest in talent to build internally-developed software to fill the gaps in marketplace offerings. Its efforts were only successful thanks to the company's software engineers and developers. However, the lack of skilled personnel was one of the biggest bottlenecks in this process.

3. A multi-disciplinary workforce and data analytics capabilities matter. The personnel implementing these technologies must include people who understand hardware, software, application development, network administration (ERP, PLM), and data management. Individuals with expertise in different software languages are often needed for in-house software development due to differences in systems (e.g. some needed Java, others C++).

Laval International

Founded in 1975 and located in Oldcastle, Ont., (near Windsor), Laval International manufactures production-ready molds, tooling, and composite parts for a range of industries including automotive, agriculture, and heavy truck, recreational vehicle, and life sciences. Laval also offers engineering and prototyping services. The company employs 60 people, the majority of whom are tradespersons. Approximately 90 percent of Laval's production is exported, primarily to the United States.

Jonathan Azzopardi became Laval's president and chief executive officer in 2009. Under his leadership, Laval has diversified its markets while engaging in extensive R&D to maintain its position as an industry leader. The company invests between 10 and 15 percent of its revenue in R&D projects.

One of Laval's current R&D projects involves implementing digital twins to support the company's flexible manufacturing capabilities. Azzopardi believes flexible manufacturing presents Canadian manufacturers with an opportunity to differentiate themselves from competitors in lower-cost jurisdictions that focus on scale.

Digital twin technology was brought to Azzopardi's attention by the Invest WindsorEssex VR CAVE. The VR CAVE is a publicly-funded virtual reality environment that serves as a teaching, training, and research facility that supports manufacturers and partners throughout Ontario. The Windsor-Essex Digital Twin Program, a collaboration between WEEDC, St. Clair College, the Canadian Association of Mold Makers (CAMM), and Automate Canada is housed within the same facility.

Laval and VR CAVE staff collaborated on a pilot project to demonstrate the potential of digital twins and virtual reality technologies to other local manufacturers. This project involved creating a digital replica of one of Laval's drill guns used to manufacture compression and injection molds. The result was a fully-immersive, interactive, and realistic representation of the gun drill that behaves exactly like its physical counterpart.

While the pilot project was the first step, Laval's medium-term goal is to develop flexible manufacturing cells that consist of several interconnected robots. Laval works on several custom molds at a time, which requires staff to devote considerable time to machine set-up, programming, loading, tool-changing, and cleaning. The envisioned flexible manufacturing cell would automate several of these activities, increasing time-to-market and streamlining production processes. A digital twin of this cell would allow Laval to produce one mold while designing and testing another virtually, leading to cost and time savings, thus allowing the company to compete more effectively with overseas competitors.

Laval is taking a step-by-step approach to digital twins. In the next six to twelve months the company hopes to develop a digital twin of one robot cell and to develop algorithms to proactively detect potential quality problems. Following this, the company plans to build digital twins of multiple robot cells and connect them, creating a full-fledged flexible manufacturing cell. This will allow the optimization of workflows and processes across the different robot cells. The company will deploy IoT sensors, vision recognition systems, and customized algorithms to build this interconnected system. The digital twin of this system is expected to help increase productivity by streamlining production scheduling and preventing equipment downtime.

Laval believes thismay require an investment of up to $500,000. However, the anticipated productivity gains and cost savings far exceed these costs. Taking this risk is worthwhile because it helps the company build long-term competitive advantages around flexible manufacturing, according to Azzopardi.

Although Laval is in the early stages the company has already identified some valuable lessons:

1. Hire talent with compatible skills. While the knowledge of the existing staff is important, Laval also relies on recent graduates with the specific skills necessary to implement digital twins in a relatively short time. The company has hired two engineers with design and software experience to work exclusively on digital twins.
2. Digital twins offer benefits to small and medium-sized manufacturers. Azzopardi says many smaller manufacturers believe digital twins are relevant only to larger companies. He disputes this, noting there are several publicly-funded programs that 'make the technology relevant to manufacturers and show it is not out of their reach.' He points to his company's collaboration with the VR CAVE as an example.
3. Start small and take measured risks. Company leaders must be willing to take risks when embarking on any project that involves emerging technologies. It can be difficult to forecast costs when the learning curve is steep. Pilot projects and staged or phased implementation can help manage risks and costs, and provide valuable learning experiences.

Insights from Technology Providers and Ecosystem Partners

Arvizio

Arvizio is a technology leader in enterprise augmented reality (AR) software for multi-user, real-time collaboration using large-scale 3D models and AR-assisted guidance employing digital twins. The company optimizes existing customer 3D models, scans, or digital twins and uses them in its AR software applications. Arvizio's software allows 3D digital replicas of physical objects, such as production equipment, to be shared through video conferencing applications. Teams working in different locations can use these digital replicas to conduct remote training and maintenance or to test alternative plant layouts before installing or removing equipment.

Arvizio's software supports a wide range of augmented and mixed reality devices like Microsoft HoloLens 2, Magic Leap, and mobile AR (iOS and Android) Recently, the company released a new product focused on delivering AR-guided instructions and training in manufacturing. This "AR Instructor" allows the creation and use of guided, step-by-step AR instructions superimposed on physical machinery in a factory to accelerate maintenance work and training. It also allows for digital twins to be used as part of the workflow creation and aims to reduce errors and increase safety with easy-to-understand visual instructions that overlay the real world.

The company notes that most of the interest it has received to date has been from North American clients. However, it has seen a recent increase in interest among European and APAC manufacturers as the result of the COVID-19 pandemic and global technology trends.

Arvizio believes that younger persons prefer learning from and working with interactive digital technologies (as opposed to print media). The company notes that its products help bridge the knowledge gap between early career professionals and those close to retirement. Arvizio software solution can be deployed over existing telecommunication networks including Wi-Fi, no additional infrastructure investment is required.

EXO Insights

EXO Insights is a Waterloo-based company that develops digital twins and simulations of high-risk, mission-critical environments where safety and precision are vital, using augmented and virtual reality technologies. The company serves the nuclear and defense industries primarily. One of the applications of their technology involves digitally replicating nuclear reactor control rooms and creating immersive simulations used to train personnel for situations that are not possible to replicate due to safety concerns. EXO also creates digital twins of humans using biometric sensors. These digital twins measure factors such as fatigue and alertness to create models to analyze performance, identify sources of errors, and improve spatial awareness. EXO observes that many manufacturers have legacy systems that become less compatible with emerging technologies over time. Digital twins can complement these legacy systems, although they may require hardware upgrades, such as IoT sensors, to be effective.

EXO's strategy involves approaching companies with dedicated digital transformation programs and staff. As the business cases for digital twins increase, interest in aerospace, medical device, and pharmaceutical industries has grown. According to EXO, those companies most interested in digital twins are primarily from industries where the financial and human cost of errors is high, and from companies where managers are genuinely interested in digital transformation.

Hive Virtual Plant

The Hive Virtual Plant, a Georgetown, Ontario-based company, builds virtual replicas of factories and production equipment to support equipment installation and removal. Hive Virtual Plant uses LiDAR scanners to generate 3D physical replicas. In addition to equipment installation and removal, the company's technology digitizes documentation related to production equipment (e.g. schematics, maintenance history) so that these documents can be accessed virtually. The company has implemented a small number of projects for manufacturers to date but generally struggles to generate new business within the sector. This is, according to the company, due to apprehension and a lack of familiarity with digital technologies among manufacturers.

Siemens

Siemens is a pioneer in digital twins and artificial intelligence (AI) technologies for manufacturing. Gorve Rekhi, of the Siemens Canada Digital Enterprise business, emphasized that digital twin technology is well-established and its application of it has enabled many benefits across industries. However, he also noted that applying digital twins requires a mindset change among companies and even entire industries. The application of digital twins requires close collaboration between the technology partner and the customer as each customer has its unique objectives and challenges. Companies, therefore, need to approach digital twins differently than other traditional automation technologies (e.g. PLCs).

Digital twins have been in use for quite a while but their capabilities and applications have evolved over the years. Traditionally they have been deployed for various applications in design and production. With the emergence of the industrial internet of things (IIoT) and applied AI, which enables capturing field data and using it for machine learning (ML), the digital twins have expanded across the product lifecycle. Manufacturers use digital twins to initially confirm the performance of a product they are developing. But they also use it to build a full virtual representation of how a product or a process performs in real life to enable the true closed-loop digital twin. Digital twins can then be extended to generate more data for ML algorithms when the operation data is not available or be used to predict failures of critical components.
The level of adoption of digital twins across the full lifecycle varies in the industry depending on the customer's level of technological maturity and the area of the business they are looking to improve.

The core requirement for closed-loop digital twins is to have the ability to represent virtually the product or process and have an accurate and comprehensive field of operation data. The objective then is to continuously provide data feedback to the digital twin to have a constant improvement loop. Manufacturers have become increasingly aware of what is possible with the data they collect. However, they may not be aware of the full range of tools that are available to help them optimize processes.

Digital twins offer significant benefits to companies operating in process-based industries such as food & beverage, oil & gas, and chemical manufacturing, according to Rekhi. Many of these companies have already invested in R&D to optimize their processes, and digital twins and artificial intelligence represent natural steps in the evolution of such companies' production technologies. In discrete manufacturing, automotive, aerospace, and machinery manufacturers have also expressed considerable interest in digital twins. For example, automotive manufacturers can leverage multi-physics simulations to test the use of new composite materials or use digital twins to confirm the performance of a new electric vehicle architecture.

These technologies are becoming increasingly affordable and accessible to small and medium enterprises (SMEs). According to Rekhi, SMEs are generally quite open and flexible; and they should be encouraged and supported to adopt innovative technologies to give them a competitive advantage. However, the lack of internal resources, like a dedicated IT team, may present hurdles for smaller companies. In such cases, SMEs can connect with external partners to get support in areas where they lack strength. However, navigating through the complex web of providers, developers, and solutions and finding the right fit is a challenge on its own.

Rekhi recommends that SMEs implement digital twins incrementally and through smaller-scale pilot projects to demonstrate value. Digital twins are scalable and offer opportunities to analyze important aspects of the business throughout the implementation process. This can help tailor the form of digital twins.

ROI varies from project to project, so it is crucial to define what success means to your project (cost reduction, waste reduction, better material flow, etc.). Use references with similar use-cases to set expectations.

Finally, Rekhi notes that implementing digital twins and artificial intelligence technologies requires support from multiple stakeholders and a collaborative mindset. These investments may take time, however, they are increasingly important to help transform businesses and prepare them for the future.

The Invest WindsorEssex VR CAVE

The Invest WindsorEssex Virtual Reality Cave Automatic Virtual Environment (VR CAVE) is Canada's largest publicly-accessible VR environment that was brought to life through the Province of Ontario's Autonomous Vehicle Innovation Network (AVIN) administered through the Ontario Centre of Innovation (OCI). Designed to support simulation testing of Ontario-based SMEs working on connected and autonomous vehicle (CAV) technologies, the use cases grew and now include supporting the province's advanced manufacturing sector. The VR CAVE serves as a teaching, training, research, and testing resource for manufacturers and other ecosystem partners.

To date, the VR CAVE has collaborated with a variety of manufacturers in the region to develop digital twin use cases and pilot projects. Simulation team members at the VR CAVE promote the use of digital twins for training as well as simulating and testing products and processes, plant layouts, design reviews, and improving customer experience. The center relies on CAD/CAM data from collaborating companies and partners to build virtual replicas and digital twins. Some of the early challenges that VR CAVE staff faced were related to software and programming language capabilities. According to the Simulation Team at the VR CAVE, developing a basic digital twin can take anywhere from three to four weeks, while a more complex and interactive application may require six months to a year to complete. A great deal was learned through the pilot program in partnership with St. Clair College, and interest continued to grow. The program is now into the second phase, where the Research and Development team at St Clair College with support from the team at the VR CAVE will assist more advanced manufacturers to embrace the benefits of digital twinning.

Discussion and Recommendations

Digital twins are an important component of Industry 4.0 and the future of advanced manufacturing. While their applications, costs, and benefits vary among manufacturers and industries there are several commonalities between companies' motivations, challenges, and implementation strategies.

Every manufacturer we spoke with was aware of the capacity for digital twins (and Industry 4.0 generally) to transform manufacturing. Moreover, they believe that digital twins were a linchpin to the adoption of other Industry 4.0 technologies and digital production technologies. They were thus willing to take some risks and commit resources to adopt and implement digital twins. Being aware of the benefits, being willing to take action, and developing an implementation plan was common to all three companies featured in this report.

The driving forces that led to the implementation of digital twins were internal, external, or both. In Avcorp's case, achieving a better understanding of a particular manufacturing process through digital twins led to production efficiencies, increased product quality, and reduced costs. In CenterLine's case, external factors, such as reduced time to market to meet customer expectations and reduced post-installation 'rework' to improve customer satisfaction and minimize costs appeared most important. At Laval, both internal and external factors proved important. The company wanted to improve the efficiency of its operations and increase flexibility as a result of increased overseas competition. The common thread across the three companies was that digital twins are a precursor to future success and competitiveness.

Several company-specific features helped even the most highly-motivated manufacturers achieve the successful implementation of digital twins. Familiarity with IoT sensors and advanced data collection and analytics were important, as were the capabilities of the existing workforce.

A supportive management team was also essential. In CenterLine's case, long-term engagement with simulation technologies helped the company implement digital twins through a series of incremental upgrades to existing systems. In Avcorp's case, the importance of parts and process traceability in the aerospace industry had already required the company to establish robust data collection systems before implementing digital twins. In Laval's case, the full support of the company's owner and CEO ensured support and resources for the project from conception to completion.

A company's capacity and willingness to invest resources to implement digital twins is crucial. While CenterLine financed its investments in digital twins on its own, Avcorp and Laval's digital twins initiatives were funded partially by government programs. In Avcorp's case, the Digital Technology Supercluster provided funding, while Laval's close working relationship with the VR CAVE helped make it aware of the potential benefits of digital twins and aided initial implementation. The latter cases demonstrate the importance of financial and non-financial support from government-funded initiatives in generating the interest and building the capacities that encourage manufacturers to invest in digital twins.

The difficulty in estimating the ROI associated with implementing digital twins remains a challenge for manufacturers. Digital twin projects involve several budget items, including hardware, software licenses, software development, and recruiting new staff. While some costs can be more easily itemized (e.g. hardware purchases), the total cost of others is more difficult to predict. The investments necessary to properly implement digital twins may also evolve alongside the project. This is especially the case for software. This level of uncertainty has slowed the adoption of digital twins by manufacturers.

The monetary value of the benefits associated with digital twins is also difficult to estimate. There are several reasons why this is the case. Isolating the benefits obtained from digital twins compared to the benefits obtained from broader investments in digitization is difficult. The same is true for certain operational efficiencies achieved throughout the implementation process. These may include the improved ability of managers to make decisions associated with a better understanding of production processes. Improvements in data collection processes may also offer wider but hard-to-quantify benefits.

Digital twins are valuable to manufacturers. That said, investing in digital twins carries some risk. To minimize these risks, manufacturers may consider some of the following practices:

Before implementation:

- Identify business needs and challenges, and ensure that digital twins can address these;
- Set goals, objectives, and a realistic timeline (preferably one with several intermediate steps);
- Estimate an expected ROI, or at least a minimum necessary ROI.
- Identify the risks associated with financial and operational requirements.
- Determine what capacities exist in-house, those that can be built in-house, and those requiring third-party assistance.
- If implementing digital twins is a medium- or long-term goal (rather than short-term), consider making investments in hardware and software that are compatible with digital twin technologies.
- Generate awareness, interest, and support among managers and staff as early as possible.
- Identify any ecosystem partners, such as universities, colleges, or other publicly-funded organizations (e.g. NGen, Digital Supercluster, IRAP, National Research Council, VR CAVE) that are familiar with and offer support at any stage of the project.

Once a manufacturer decides to implement digital twins:

- Start at the beginning. Identify potential pilot projects. Scale-up incrementally and based on experience and lessons learned in pilot projects.
- Seek to continuously improve data collection and analytics capabilities, including those that seem conceptual. These will be critical to successful implementation.
- Recruit and develop personnel with digital twins in mind.
- Encourage collaboration among key internal stakeholders, especially across departments and/or divisions (e.g. IT and production/operations).
- Identify capabilities within existing suppliers, customers, and collaborators.
- Train staff in parallel with implementation, and break the project into phases to help keep pace with training.

Conclusion

Digital Twins are increasingly seen by manufacturers of all sizes as an important tool to drive productivity improvements. It can help manufacturers to replicate a physical object or process and produce valuable insights and information. Well-designed Digital Twins have the potential to become a single source of truth and enable traceability. SMEs who bravely pave the path in investing in digital twins are more likely to leapfrog the competition. The case studies presented in this report are a few examples of how Canadian manufacturers have used Digital Twins in their digital transformation journey.

Organizations like NGen and the Trillium Network see digital twins as an opportunity to improve Canada's manufacturing sector. Increased adoption of digital twins can also help increase the adoption rates of IoT, AI, VR, Blockchain, and other advanced manufacturing technologies. Investing wisely in such technologies can help Canadian manufacturers and our technology companies to collaborate and grow Canada's prominence in advanced manufacturing.

Statistics Canada studies show that Canadian businesses are keen on optimizing their existing processes and introducing new process technologies. Digital twins, as seen in the case studies, can play a critical role in this process optimization effort. Organizations like NGen are here to raise awareness, enable collaborations, and potentially provide financial support to drive advancements in advanced manufacturing technologies and grow Canada's advanced manufacturing sector. NGen's Canada-wide member network and its partnership with the Trillium Network can be useful resources to find partners in the digital transformation journey.

Placing due attention on data privacy, data security, and interoperability issues is critical to the success of any Digital Twins initiative. When considering implementing Digital Twins, it is important to focus on a company-wide transformation that offers extensive benefits and a potentially significant ROI. Several thought leaders see Digital Twins as the beginning of the Industrial Metaverse. It is time for us to act now and be at the forefront of developing and adopting these advanced technologies, optimizing our manufacturing processes, and securing our manufacturing future.

Endnotes

i Grieves, M. and Vickers, J. (2016). 'Digital Twin: Mitigating unpredictable, undesirable emergent behavior in complex systems' in F.-J. Kahlen et al. (eds.) Transdisciplinary Perspectives on Complex Systems, 85–113. https://doi.org/10.1007/978-3-319-38756-7_4

iiShafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne and J., Wang, L. (2010). DRAFT Modeling , Simulation , Information Technology & Processing Roadmap. National Aeronautics and Space Administration, 11-27. https://www.nasa.gov/pdf/501321main_TA11-MSITP-DRAFT-Nov2010-A1.pdf

iii Neto, A. A., Deschamps, F., da Silva, E. R., and de Lima, E. P. (2020). Digital Twins in manufacturing: An assessment of drivers, enablers and barriers to implementation. Procedia CIRP, 93, 210–215. https://doi.org/10.1016/j.procir.2020.04.131

iv Tao, F., Zhang, H., Liu, A., and Nee, A. Y. (2019). Digital Twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405–2415. https://doi.org/10.1109/tii.2018.2873186

v Shen, Z.-J. M., Wang, L., and Deng, T. (2021). Digital Twin: What it is, why do it, related challenges, and research opportunities for Operations Research. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3777695

vi Sharma, A., Kosasih, E., Zhang, J., Brintrup, A. and Calinescu, A. (2020). Digital Twins: State of the Art Theory and Practice, Challenges, and Open Research Questions. ArXiv. Preprint. https://arxiv.org/abs/2011.02833

vii Tao, F., Zhang, H., Liu, A., and Nee, A. Y. (2019). Digital Twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405–2415. https://doi.org/10.1109/tii.2018.2873186

viii https://www.mayahtt.com/success_story/Electra%20Meccanica%20-

ix https://bioprocessintl.com/bioprocess-insider/therapeutic-class/podcast-gsks-digital-twin-approach-to-vaccine-development/

x https://www.prnewswire.com/news-releases/gastops-to-support-uscg-ice-breaker-service-life-extension-with-propulsion-system-digital-twin-design-301316230.html

xi Lu, Y., Liu, C., Wang, K. I.-K., Huang, H., and Xu, X. (2020). Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. Robotics and Computer-Integrated Manufacturing, 61, 101837. https://doi.org/10.1016/j.rcim.2019.101837

xii https://www.steptools.com/

xiii https://new.siemens.com/global/en/products/automation/systems/sinumerik-one/sinumerik-one-for-machine-users.html

xiv https://www.ey.com/en_ca/advanced-manufacturing/how-digital-twins-give-automotive-companies-a-real-world-advantage

xv https://www.sme.org/technologies/articles/2021/april/braskems-use-of-digital-twin-exemplifies-society-5.0/

xvi https://www.kruger.com/news/25m-investment-to-implement-cutting-ede-ai-capabilities-at-kruger-products-sherbrooke-plant/