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Extending the lean value stream mapping to the context of Industry 4.0: an agent-based technology approach

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ABSTRACT

With the advancement of the 4th industrial revolution and its enabling technologies, researchers and practitioners discuss the mutual relationships and integration of Lean manufacturing with Industry 4.0 to enhance the manufacturing sector's competitiveness. However, the literature falls short on how Lean principles and practices can support Industry 4.0. To contribute to reducing this research gap, this study explores the integration of the Lean practice Value Stream Mapping (VSM) with Hybrid Simulation (HS) that combines discrete event and agent-based modelling and simulation. It aims to extend VSM scope to the context of Industry 4.0 to help Industry 4.0 initiatives in manufacturing companies, especially in small and mid-size enterprises (SMEs), wherein managerial approaches are still scarce, enabling it to capture the behaviour of more complex entities and distributed production systems. An HS-VSM framework is proposed, and its use is demonstrated through a proof-of-concept case developed in an SME from the furniture and related product manufacturing sector in Quebec, Canada. This study indicates that VSM combined with HS can assist Industry 4.0 roadmap development and help companies understand changes in materials, equipment, processes, and information flows associated with Industry 4.0 application scenarios.

1. Introduction

Derived from Toyota Production System and popularised by Womack et al. (1990), Lean manufacturing (LM) became a central managerial approach to improve companies' operational performance, e.g. cost, quality, flexibility, and delivery (Negrão et al., 2017). It is considered a multidimensional approach that encompasses over 40 management practices, such as value stream mapping, continuous improvement, and levelled production (Marodin and Saurin, 2013). Furthermore, its implementation has proven to be effective in different companies over different business sectors to increase value-added work by reducing waste throughout value chains (Shou et al., 2017).

With the advancement of Industry 4.0 (I4.0) and its enabling technologies (e.g. cobots, internet of things, big data, artificial intelligence, modelling and simulation), researchers and practitioners from industrial engineering and operations management fields discuss the mutual relationship (e.g. LM supports I4.0, I4.0 supports LM) and integration of LM with I4.0 to enhance companies' competitiveness (Buer et al., 2018, 2021; Tortorella et al., 2021). A survey conducted with 465 Brazilian companies reveals that the concurrent implementation of LM and I4.0 positively impacts companies' operational performance (Tortorella and Fettermann, 2018). Likewise, a survey conducted with 108 European manufacturers suggests that companies aiming to adopt higher levels of I4.0 should concurrently implement LM for superior performance results (Rossini et al., 2019). While there have been numerous studies on how I4.0 can support LM, studies investigating the facilitating effects of LM on I4.0 implementation, such as procedural/prescriptive methods for the adoption of I4.0 related technologies, are still scarce (Ciano et al., 2021).

Along the same line, there is still a lack of methods and tools to help companies transition to I4.0 (Hofmann and Ruesch, 2017), principally for small and medium-sized enterprises (SMEs) (Masood and Sonntag, 2020). Indeed, several authors suggest that more research is needed to help companies identify areas of their business that could be improved through I4.0 principles and technologies and how they should be implemented to overcome initial barriers, such as the lack of knowledge, infrastructure, and financial resources (Schneider, 2018; Fettermann et al., 2018; Müller et al., 2018; Stentoft et al., 2020; Masood and Sonntag, 2020). In this context, a longitudinal case study conducted in a manufacturing SME reveals that the I4.0 transition process can begin with digitising certain areas of operation (Ghobakhloo and Fathi, 2019). In the same direction, Buer et al. (2020) suggest that SMEs should approach the adoption of I4.0 technologies incrementally through small-scale projects. Nevertheless, methodologies to help SMEs spot and analyse opportunities for developing I4.0 initiatives are still missing in the literature.

Value stream mapping (VSM) is the main mapping tool used by the LM community and the first practice to be

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put in place to deploy LM in companies (Andreadis et al., 2017). It facilitates the systematic identification of waste and supports decision-making for prioritising and coordinating continuous improvement initiatives by providing a holistic view of the value streams performed to deliver a product or service to customers (Shou et al., 2017). Different approaches to extend VSM to I4.0 have been proposed. As an example, general guidelines for VSM design integrating I4.0 technologies are provided in Tortorella et al. (2020). In addition, a literature review and empirical survey conducted with 170 Lean experts on the future adequacy of VSM points to modelling and simulation as key technologies to enhance VSM and extend its use to I4.0 context (Lugert et al., 2018). However, non of the existing approaches enables VSM to assess I4.0 production scenarios comprehensively.

In line with that, limited efforts integrating VSM with hybrid simulation (HS) that combine discrete-event simulation (DES) with agent-based modelling and simulation (ABMS) exist in the literature, and which is considered an essential technology able to capture I4.0 requirements (de Paula Ferreira et al., 2020). This study aims to extend VSM to the context of I4.0 to support I4.0 initiatives in manufacturing companies by integrating it with HS.

The main contribution of this study is a framework to extend the Lean practice VSM to the context of I4.0, enabling it to capture the behaviour of more complex entities and distributed production systems considered in the context of I4.0. It proposes a hybrid simulation-based value stream mapping (HS-VSM) approach that combines VSM with ABMS and DES to support I4.0 initiatives in manufacturing companies, especially SMEs, facilitating the analysis of VSM encompassing I4.0 production scenarios. The framework is tested through a proof-of-concept case conducted in a manufacturing SME located in Quebec, Canada.

The remainder of this paper is organised as follows. Section 2 provides a background on the related work. Section 3 presents the research design. The modelling framework is described in Section 4, and the proof-of-concept case is presented in Section 5. Finally, the main findings of this study, limitations, and avenues for follow-up research are reported in Section 6.

2. Literature Review

This section first introduces the concept of I4.0 and looks at the application of I4.0 from the perspective of manufacturing SMEs. Then, it highlights the use and importance of modelling and simulation for I4.0 and reviews the literature combining the Lean practice VSM with simulation modelling and exploring its use in the I4.0 context.

2.1. Industry 4.0 in SMEs

I4.0 is considered a central strategy to innovate and increase the manufacturing sector's competitiveness in an increasingly digital global economy. It is mainly associated with design principles (e.g. modularity, flexibility, agility, virtualisation, decentralisation, autonomy) and technologies, having implications for value creation, business models, work organisation, and performance (de Paula Ferreira et al., 2020). It "will lead to the emergence of dynamic, real-time optimised, self-organising value chains that can be optimised based on criteria such as cost, availability, and resource consumption" (Kagermann et al., 2013, p. 20). There are over 100 definitions of I4.0 in the literature, as underlined in Culot et al. (2020), but "technically, Industry 4.0 represents the fusion of IT (Information Technology) and OT (Operational Technology)" (Adolph et al., 2020, p. 1).

Examples of IT include the internet of things (IoT), cloud computing, big data, and simulation. Examples of OT include supervisory control and data acquisition (SCADA), distributed control system (DCS), programmable logic controllers (PLCs), smart gateways, and smart sensors (Morgan et al., 2021). In line with that, this study takes as a reference the 17 principles characterising I4.0 described in de Paula Ferreira et al. (2020) and the list of 112 technologies related to I4.0 presented in Gartner (2020), classified by deployment stage, risk and enterprise value, which can be combined in different I4.0 scenarios for application (Anderl et al., 2016).

SMEs are increasingly interested in transitioning towards I4.0, whether driven by internal motivation or by pressure from customers and or large companies, such as from Original Equipment Manufacturers, fearing being forced out of the market if they do not comply with their requirements (Müller et al., 2018). The empirical survey conducted by Masood and Sonntag (2020) indicates that not just the motivations, challenges, and priorities of SMEs to adopt I4.0 are different compared to large companies, but that SMEs concentrate more on cost reduction and short-term benefits (e.g., flexibility, efficiency). As highlighted in another empirical survey, there are different ways for approaching I4.0, "for many SMEs it is a sum of adaptions, for larger companies it can be a real manufacturing revolution" (Müller et al., 2018, p. 6). Nevertheless, there is still a lack of I4.0 practice-enhancing research – encompassing the development and assessment of use cases and knowledge-enhancing research – concerning implementation strategies and roadmaps (Schneider, 2018), principally for SMEs, where most tools and frameworks do not go beyond giving an I4.0 readiness/maturity state of an organization (Masood and Sonntag, 2020).

2.2. Modelling and simulation in Industry 4.0

Modelling and simulation are key enabling technologies of I4.0 (de Paula Ferreira et al., 2020). They apply throughout the product's entire life cycle (e.g. design, production) and are essential to managing increasingly complex manufacturing systems (Kagermann et al., 2013). The state-of-the-art review on simulation in I4.0 conducted by de Paula Ferreira et al. (2020) describes several simulation-based approaches employed in the context of I4.0, of which hybrid simulation (HS) that combines discrete-event simulation (DES) and agent-based modelling and simulation (ABMS) is one of the main approaches adopted in the literature. This

Table 1
Literature on simulation-based VSM

Reference	Main contribution	Simulation method		
		DES	SD	ABMS
McDonald et al. (2002)	Using simulation to enhance VSM	✓		
Abdulmalek and Rajgopal (2007)	Analysing Lean production and VSM benefits via DES	✓		
Lian and Van Landeghem (2007)	A simulation-based VSM (SimVSM) approach	✓		
Agyapong-Kodua et al. (2009)	Modelling dynamic VSM in aid of process design	✓	✓	
Xie and Peng (2012)	Integrating VSM with ABMS to model human behaviour			✓
Helleno et al. (2015)	VSM with DES as a decision-making tool	✓		
Atieh et al. (2016)	VSM with multiple evaluation approaches	✓		
Stadnicka and Litwin (2019)	An extended VSM (VSMap) approach		✓	
Oleghe and Salonitis (2019)	Integrating VSM with SD and DES	✓	✓	
Arndt et al. (2019)	VSM with HS for quality control in manufacturing networks	✓		✓
de Assis et al. (2021)	A practical framework for translating VSM into SD models		✓	
This study	Integrating VSM with HS to support Industry 4.0 initiatives in companies	✓		✓

DES - Discrete Event Simulation; SD - System Dynamics; ABMS - Agent Based modelling and Simulation; HS - Hybrid Simulation.

is reinforced by dos Santos et al. (2021), which explored the use of HS as an alternative to design digital twin to aid decision-making in production processes and consistent with Negahban and Smith (2014), which describes the use of HS to optimise manufacturing systems operations.

It is worth mentioning that agent technology, which encompasses ABMS, is of central importance in the context of I4.0 due to its capability to meet I4.0 requirements (e.g., modularity, decentralisation, autonomy) and represent I4.0 components, i.e., an asset plus an administration shell that refers to an asset's data-warehouse, which is considered the basic element for I4.0 systems (Salazar et al., 2019). Moreover, it is considered a realistic solution for the realisation of I4.0 architectures (Vogel-Heuser et al., 2020). Therefore, it may have an empowering effect on Lean practices (e.g., VSM), helping overcome some of its limitations in dealing with more complex and distributed systems and represent I4.0 production scenarios, which is still unexplored in the literature (Uriarte et al., 2020).

2.3. Simulation-based VSM

Lean VSM has been evolving over time, reflecting the need of different business sectors and the ongoing trends of increasingly complex manufacturing systems (Shou et al., 2017). It has been enhanced mainly through simulation modelling technologies (Uriarte et al., 2020). Table 1 presents a list of key original research articles on simulation-based VSM, including a brief description of the studies' main contributions and an analysis of the application of major simulation modelling methods used in industrial engineering and operations management fields, i.e. System Dynamics (SD), DES, ABMS, and HS (Scheidegger et al., 2018).

McDonald et al. (2002) are among the first ones to use DES to enhance VSM, addressing its static limitations. Abdulmalek and Rajgopal (2007) followed a case-based approach to demonstrate the application of Lean production to the process sector, using VSM combined with DES to analyse system configurations and Lean performance measures in a large integrated steel mill company. Lian and Van Landeghem (2007) proposed a simulation-based approach (SimVSM) that combines object-oriented modelling with a model generator to yield DES models of VSM automatically. Other real cases demonstrating the effectiveness of integrating VSM with DES in different contexts are reported in Helleno et al. (2015) and Atieh et al. (2016).

Agyapong-Kodua et al. (2009) combined VSM with SD modelling and DES to develop a dynamic VSM for experimenting with alternative policies to support process design in complex manufacturing systems with multiple product flows. Similarly, Stadnicka and Litwin (2019) proposed the extended VSM (VSMap), integrating VSM with SD modelling and simulation for manufacturing line modelling and analysis. Oleghe and Salonitis (2019) developed an HS (SD + DES) approach to evaluate the interactions between human factors and process flow elements and assess non-tangible aspects in Lean production systems. de Assis et al. (2021) introduced a practical framework for translating VSM into SD models based on two leading SD modelling tools available on the market (i.e. Vensim® and STELLA®).

The systematic literature review on the combination of Lean practices with simulation conducted by Uriarte et al. (2020) reveals that the main Lean practice combined with simulation is VSM and that the majority of studies combines VSM with a DES approach. They also reveal an increasing trend in integrating VSM with SD and that the integration of Lean practices with ABMS and HS approaches still need to be explored. Moreover, they highlight that there is still a "lack of comprehensive frameworks in the combination of Lean and simulation", especially in the context of I4.0 (Uriarte et al., 2020, p. 112). This study aims to contribute to this literature by examining the integration of VSM with HS that combines DES with ABMS to support companies transition towards I4.0, where practice-oriented approaches are still missing (Masood and Sonntag, 2020).

2.4. VSM in the context of Industry 4.0

Lugert et al. (2018) conducted a systematic literature review and empirical survey with 170 Lean experts (both researchers and practitioners from different industrial sectors) to assess VSM's current status and future development needs. Their findings indicate that the Lean VSM method needs to gain more flexibility to cope with the ongoing digitalisation and suggest that VSM can support I4.0 and be enhanced by I4.0 technologies. In line with that, Tortorella et al. (2020) developed general guidelines for VSM design integrating I4.0 technologies. Their results suggest that I4.0

Table 2
Literature on Lean VSM in the context of Industry 4.0

Reference	Research method	Main contribution
Lugert et al. (2018)	Literature review and empirical survey	Assesses the future adequacy of VSM for Industry 4.0 context through a literature review and survey with 178 Lean experts.
Tortorella et al. (2020)	Literature evidence and experts' opinion	Presents general guidelines for design VSM integrating Industry 4.0 technologies.
Meudt et al. (2017)	Framework	Introduce the VSM 4.0 that integrates VSM with an information-logistic waste system.
Hartmann et al. (2018)	Framework	Improves the VSM 4.0 for value stream design.
Busert and Fay (2019)	Framework	Presents an extended VSM for information based improvement of production processes.
Ramadan et al. (2017)	Modelling and simulation	Proposes a real-time manufacturing cost tracking system (RT-MCT) that integrates VSM with RFID technology.
Chen (2017)	Modelling	Elaborates an intelligent VSM-based food traceability cyber-physical system approach.
Huang et al. (2019)	Experimental study	Develops a cyber-physical multi-agent system (CP-MAS) for dynamic VSM.
Lu et al. (2021)	Design science	Presents a digital twin-enabled VSM method for production process redesign and reengineering.
This study	Design science	Introduces a framework that combines VSM with discrete-event and agent-based modelling and simulation to support Industry 4.0 initiatives in manufacturing companies, especially SMEs.

technologies can enhance VSM design and reveal links between VSM design guidelines and I4.0 technologies.

Meudt et al. (2017) introduced the VSM 4.0 framework to improve the visualisation and analysis of the current state VSM by integrating the VSM with key performance indicators data from different IT-systems, such as Information Logistic Waste and Manufacturing Executing Systems. Their results suggest that VSM 4.0 can support value stream analysis in I4.0 environment based on digital information and help define current production processes' information handling and utilisation. Hartmann et al. (2018) enhanced the VSM 4.0 procedure to support value stream design (i.e. future state) to help identify production processes' classical and information wastes and design lean value streams, especially in terms of information flows. Similarly, Busert and Fay (2019) proposed a new procedure based on an extended VSM approach that incorporates advanced information flow elements to drive information-based improvements for production and logistics processes considering information flow quality and harmonisation.

Ramadan et al. (2017) developed a real-time manufacturing cost-tracking system (RT-MCT) framework that combines a dynamic VSM with RFID technology. Their framework enables identifying redundant costs, estimating the cost of non-value-added activities, and providing a cost-time profile to support decision-making for continuous improvement efforts. Chen (2017) developed an intelligent VSM-based food traceability cyber-physical system (CPS) approach to optimise the performance of food traceability systems, combining VSM with IoT, CPS, enterprise architecture, and EPCglobal via fog computing network. Their results suggest that Lean VSM integrated with IoT-enabled CPS can enhance the collaborative efficiency of agriculture food traceability systems. Huang et al. (2019) developed a cyber-physical multi-agent system (CP-MAS) for dynamic VSM, suggesting that VSM based on CP-MAS can reflect dynamic, non-linear material value flows, common in complex production systems. Lastly, Lu et al. (2021) presented a digital twin-enabled VSM method for production process' redesign and reengineering.

Table 2 summarises the literature on the use of Lean VSM in the context of I4.0, including their research method and main contribution. It is important to note that none of these studies provides a framework or general guidelines on modelling VSM based on agent technology or using VSM combined with hybrid simulation (ABMS + DES) to support the development of I4.0 initiatives in manufacturing SMEs. In this study, I4.0 initiatives refer to projects carried out by SMEs seeking to move towards I4.0, which involve the application of one or more I4.0 design principles and technologies characterising or enabling the realisation of I4.0 application scenarios or examples, such as order-controlled production, operator support in production, adaptable factory and self-organising adaptive logistics (Anderl et al., 2016).

3. Methodology

This study adopts the Design Science Research (DSR) methodology (see Fig. 1), described in Hevner et al. (2004), to assure practical relevance and scientific rigour in developing the HS-VSM framework. With thousands of citations in different databases (e.g., Web of Science, Scopus, Google Scholar), the DSR has become a well-accepted research paradigm in information systems and engineering domains to support the development of new artefacts (e.g., systems, applications, algorithms, models, frameworks) that can be applied to "the solution of real-world problems or to enhance organisational efficacy" (Peffers et al., 2018, p. 129).

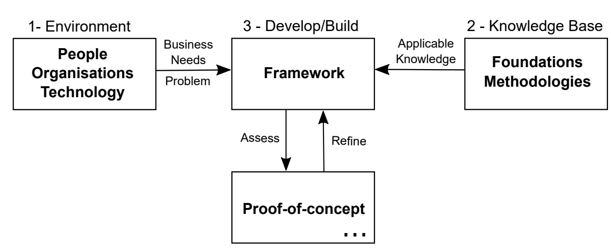


Figure 1: Deign Science Research framework
Source: Adapted from Hevner et al. (2004)

As summarised in Fig. 1, a design cycle of artefact development starts with awareness of business needs or a problem, as perceived defined by the researcher. Then, possible solutions are derived from the existing knowledge base of the problem space, composed of foundations (e.g., constructs, theories, frameworks, methods, models) and methodologies.

After that, assessment (e.g. simulation, proof-of-concept, empirical studies) and refinement processes are performed. The latter is often described in future research directions and recommendations, performed in a new design cycle in a new study (Hevner et al., 2004).

After defining the research problem from the technical procedures, the research starts with a literature review. Next, the HS-VSM framework is designed. Then, it is evaluated through a proof-of-concept case developed in a manufacturing SME (i.e. with 1 to 99 employees) located in the province of Quebec, Canada, that produces cabinets for the residential, renovation, and commercial sectors. This company was chosen for developing the proof-of-concept case mainly because they are engaged in the transition to I4.0, and they are participating in a governmental program that aims to increase the competitiveness of the Canadian manufacturing sector and just received a grant.

4. HS-VSM framework

Fig. 2 gives an overview of the model-based VSM approach adopted in this study to support I4.0 initiatives in manufacturing SMEs using the unified modelling language (UML) activity diagram that is similar to a flowchart. The first step is to design the conventional current state VSM, following Rother and Shook (2003) guidelines and, if needed, its extensions such as the multi-method VSM for high-variety product environment with complex and concurrent flows described in Duggan (2018), or the extended VSM for multiple plants or across company described in Jones et al. (2011), depending on the system under analysis.

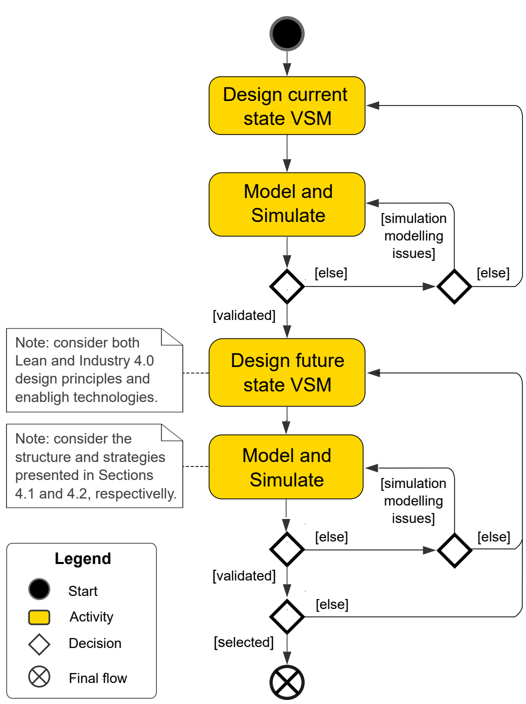


Figure 2: UML activity diagram of the proposed approach

The second step is to model and simulate the current state VSM. For this, a discrete-event agent-based framework for VSM modelling and simulation is proposed in this study, described in the next section. It is important to highlight that the current state VSM, which includes process data (e.g. working time, cycle time, setup time, number of operators), and its corresponding simulation model must be analysed and validated in conjunction with the company's domain experts. It ensures model validity (e.g. material and information flow, system behaviour), project team member engagement, and consensus decision-making.

Next, the future state VSM is designed, modelled, and simulated observing Lean principles, practices, and metrics, as described in Marodin and Saurin (2013), and I4.0 design principles and enabling technologies to generate I4.0 scenarios, as described in de Paula Ferreira et al. (2020), aiming to improve companies' operational performance. The use of ABMS in an HS approach enables modelling I4.0 components and augmenting the Lean VSM to assess opportunities for digitalisation in production processes. It is important to mention that this iterative process requires constant exchange between modellers, domain experts, and other stakeholders involved in the I4.0 transformation. The VSM simulation models can be either deterministic or stochastic. However, HS-VSM will typically involve stochastic variables and models to better capture processes' inherent variability and uncertainties associated with value streams.

The guidelines proposed by Tortorella et al. (2020) to design VSM integrated with I4.0 technologies apply to this stage depending on the I4.0 application scenarios considered since it envisions the incorporation of I4.0 related technologies into each of Rother and Shook (2003)'s traditional Lean VSM guidelines. Summarised, Tortorella et al. (2020)'s technology-integrated VSM guidelines are as follows: (1) define real-time takt; (2) constant adaptation of finish goods strategy; (3) implement highly flexible continuous flow; (4) establish monitorable and flexible first-in-first-out; (5) determine transient supermarket; (6) create multiple-point scheduling; (7) constantly define interval; (8) determine and remotely manage pitch. A company's I4.0 maturity/readiness assessment results can also provide insights for designing the future state VSM since it enables prioritising maturity dimensions and items for development.

Lastly, the selected future state VSM serves as an input to the I4.0 roadmap development process flow. It is worth mentioning that other simulation-based approaches such as computer-aided technologies and virtual commissioning can be used in later stages of I4.0 roadmap development. They can be used to build planning and explanatory models able to translate the changes proposed in the future state VSM from high abstraction levels to low abstraction levels and technical specifications for implementation in companies (de Paula Ferreira et al., 2020).

A simulation project is usually divided into three phases (Scheidegger et al., 2018). The conception phase consists of developing and validating a conceptual model that captures the requirements of the problem (or system) under analysis, while the implementation phase consists of developing, verifying, and validating the computational model. In the analysis phase, computer experiments' results are analysed, validated, and communicated to stakeholders. Section 4.1 presents a strategy for the conception phase and Section 4.2 for supporting the implementation and analysis phase.

4.1. Modelling

Lean VSM relies mainly on a set of standardised icons representing different manufacturing and logistics components to map value streams for a product family at different magnification levels. Rother and Shook (2003) describes the conventional Lean VSM at the process and single-plant levels that entail door-to-door material and information flow from receiving to shipping within a facility. Jones et al. (2011) describe the extended VSM that covers multiple plants and across company levels. Based on its characteristics, we can define these icons (building blocks) as software agents for VSM modelling and simulation, enabling capturing complex internal behaviours of entities in distributed systems. An agent is "an autonomous component that represents physical or logical objects in the system, capable to act in order to achieve its goals, and being able to interact with other agents, when it does not possess knowledge and skills to reach alone its objectives" (Leitão, 2009, p. 982). The advantage of integrating ABMS and DES with VSM is that it enables the representation of I4.0 components as described in Salazar et al. (2019) and the dynamic analysis of VSM for complex production systems, including features characterising I4.0 such as decentralisation, modularity, reconfigurability, autonomy, flexibility, and agility (Karnouskos et al., 2020).

This study proposes five basic agents (see Fig. 3) for modelling VSM at its different magnification levels: product agent (PA), resource agent (RA), order agent (OA), coordination agent (CA), and facility agent (FA). They can be aggregated and or specialised to reflect both hierarchical and heterarchical manufacturing systems. The description of its roles, functions, and responsibilities is summarised in Table 3. They are based on the product, operational, task, and supervisor holons that form holarchies from the ADAptive holonic COntrol aRchitecture (ADACOR) for distributed manufacturing systems (Leitão and Restivo, 2006), which in turn derive from the holonic manufacturing systems defined in the Product-Resource-Order-Staff (PROSA) reference architecture (Van Brussel et al., 1998). It relates to the "structure of LEGO® products, where generic building blocks are provided, enabling the development of any possible construction, without specifying how the future construction should look" (Van Brussel et al., 1999, p. 40).

The correspondence between the hierarchy levels defined in RAMI4.0, i.e. the reference architecture model for I4.0 (DIN SPEC 9134, 2016), and VSM levels are also depicted in Fig. 3. It is also possible to specialise the basic agents to meet the requirements of each layer (axes 2) of RAMI4.0 as described in Salazar et al. (2019) and analyse its life cycle. However, it is beyond the scope of this paper that focusses on simulation modelling and manufacturing systems improvement and redesign.

RAMI4.0 is a framework used to logically describe assets and their combination, which compose I4.0 systems, using a level model (DIN SPEC 9134, 2016), while VSM is a framework used to support asset management that refers to "the coordinated activity of an organisation to realise value from assets in the asset life cycle" (van Nierop, 2017, p. 5). Therefore, they can be complementary. Assets in the context of I4.0 are objects of value for an organisation, whether tangible or not (i.e. physical or virtual objects) such as a whole manufacturing facility or part of it (DIN SPEC 9134, 2016), represented by the basic agents in our framework to some extent. The hierarchy levels axis of RAMI4.0, which is an extension of ISA-95 hierarchy levels, serves for allocating functional models to particular levels, representing I4.0 environments.The point here "is not implementation, but solely functional assignment"(Adolphs et al., 2015, p.10).

The connected work level (see Fig. 3) refers to a collection of enterprises (e.g. manufacturing supply chain network) and relates to VSM across companies level. The enterprise level refers to a collection of facilities (or sites) and relates to VSM at a multiple plants level. The work centres level refers to a logical grouping of resources determined by a facility and relates to VSM at a single plant level. The other levels (i.e. station, control device, field device, and product) serves to realise classifications within a facility and relates to VSM at a process level.

4.1.1. Example cases

The basic agents can be specialised or aggregated to model VSM at its different magnification levels in a way that enables the analysis of several I4.0 scenarios. Fig. 4 illustrate four example cases related to I4.0 scenarios using simplified collaboration diagrams. However, the number of possible configurations and I4.0 examples and application scenarios are countless.

Fig. 4a presents a model for VSM at a process level. This scenario considers a robotic arm and two CNC cutting machines (i.e. specialised resource agents) grouped into a workstation (aggregated agent), representing a cutting process. After receiving a work order, a CNC cutting machine negotiates with the handling robot for loading or unloading a workpiece. This modelling approach enables the analysis of internal behaviours and dynamics of processes represented by a process and data box icons in the VSM and the analysis of more distributed systems considered in I4.0.

Fig. 4b represents a model for the VSM at a single plant level, related to the I4.0 scenario of order-controlled production, as described in Anderl et al. (2016). Once a customer order enters the system, an order agent requests a process plan from the product agents and a schedule from the coordination agent, then requests resource agents processing (e.g. machining, transportation) until it reaches its final state. In a kanban pull system, a coordinator agent can also act for levelling production. Another I4.0 application scenario that

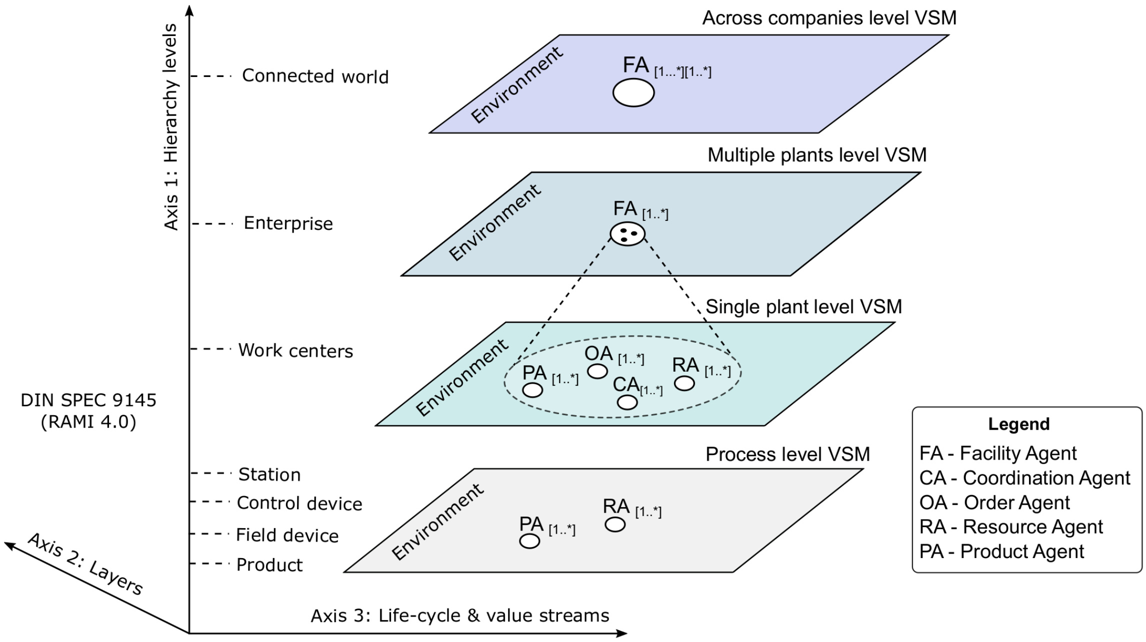


Figure 3: Basic agents for modelling and simulating VSM at its different magnification levels

Table 3
Description of basic agents

Agent type	Description
Product Agents (PA)	They represent the different products and the knowledge to produce them (e.g. product structure, process plan), corresponding to a particular product or product family selected for analysis in a VSM, wherein a data box represents it. They are also responsible for checking if all parts and raw materials of a product are available in the system. They can be divided (specialised) into sub-products or components.
Resource Agents (RA)	They represent the different resources presented in a manufacturing or logistics system, providing production capacity and functionality to the other agents, mainly represented by an icon of a process and data box in a VSM. They may also represent human resources, e.g. an operator. Each RA is responsible for deliberating and processing assigned tasks, managing and monitoring machine operations and inventory. They are also responsible for the shipments to customers or between facilities, represented by the plane, train, and truck shipment icons (Jones et al., 2011).
Order Agents (OA)	They coordinate the operations of a particular order, interacting with coordination, product, and resource agents for services to complete the order. It may represent different types of orders, such as customer orders, stock orders, production or work orders, which can be divided or grouped into batches. In the VSM, the OA is represented by a data box, information flow, and production kanban icons.
Coordination Agent (CA)	It is responsible for coordinating the operations of all orders, handling global tasks of the system, enabling establishing hierarchies and centralised structures in decentralised systems to achieve global production optimisation. It is based on the supervisor holon from ADACOR (Leitão and Restivo, 2006), which has self-organisation capability, allowing hierarchical and heterarchical control architectures. The CA can also be used to coordinate operations between facilities. In the VSM, the CA covers the functions of the production control, schedule, and Heijunka box icons.
Facility Agent (FA)	It represents the different facilities composing a multi-echelon supply chain network, such as the factory, cross-dock, and warehouse icons in the extended VSM (Jones et al., 2011). Each FA aggregates PA, RA, OA, and CA, which can be used to extend the scope of analysis beyond shop floor level.

can be explored here is operator support in production and adaptable factory (Anderl et al., 2016) as in reconfigurable and adaptive production systems that can self-organise after a resource is added or removed (Kim et al., 2020).

Fig. 4c represents a model for the VSM at multiple plants level, such as for a company with two or more production plants (i.e. facility agents) that provide services to each other to fulfil an order. In this case, a facility agent can take either the role of manager (initiator) or contractor, considering the CNP. In this context, another I4.0 application scenario that can be evaluated is the self-organising adaptive logistics (Anderl et al., 2016).

Lastly, Fig. 4d represents a model for the VSM at across-companies level, such as for the example provided in Jones et al. (2011), which involves suppliers, production plants, cross-dock, and distribution centres from more than one company, represented by facility agents. A coordination agent can be added to prevent a ripple effect or to enable I4.0 scenarios related to crowdsourced manufacturing, acting as a collaboration platform as described in Kádár et al. (2018). Other I4.0 application scenarios that can be investigated in this setting are self-organising adaptive logistics, transparency, and adaptability of delivered products (Anderl et al., 2016).

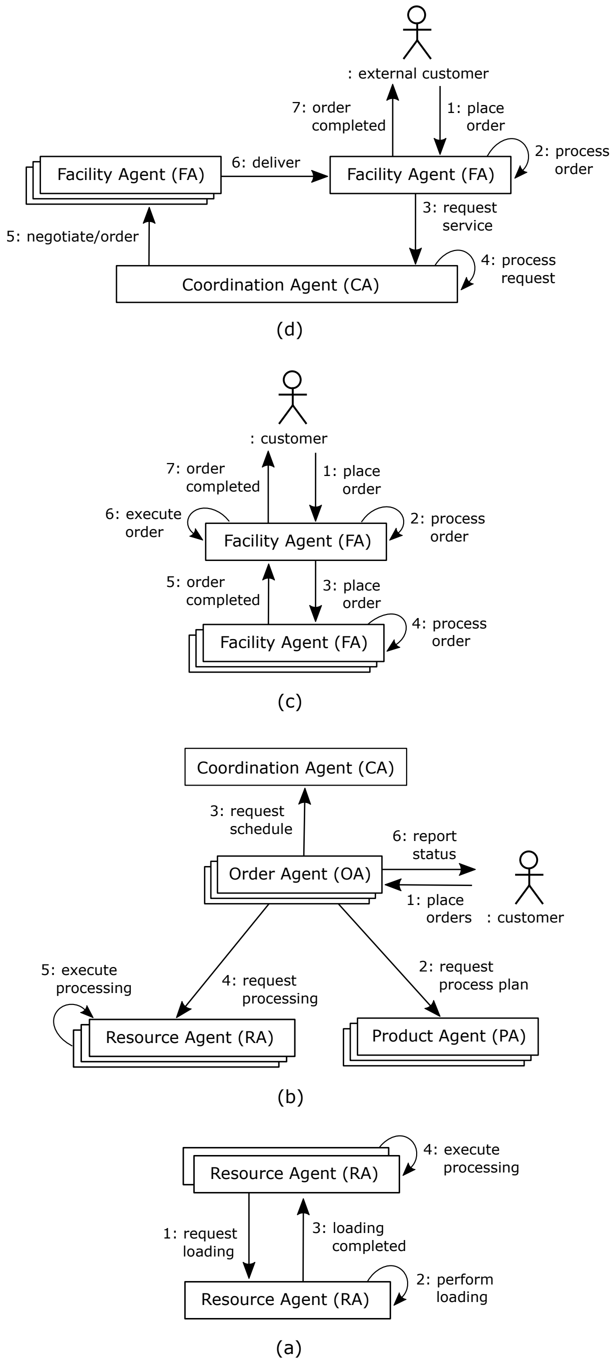


Figure 4: Example cases of basic agents' interactions related to: (a) process level VSM. (b) single plant level VSM. (c) multiple plants level VSM. (d) across-companies level VSM.

4.2. Implementation and analysis

In order to provide more practical guidelines for simulation experts and practitioners on the implementation of the HS-VSM approach, this study highlights three main strategies for developing the VSM models (i.e. DES, DES+ABMS, ABMS) as shown in Fig. 5. The commercial multi-method simulation modelling platform AnyLogic was chosen to illustrate the application of these strategies since it "is the most widely utilised tool for building HS models" (Brailsford et al., 2019, p. 730). However, the proposed model-based VSM approach in this study is platform-independent.

Fig. 5a shows a sole agent-based model that can be used to simulate VSM at all mapping levels since it follows a bottom-up approach to model complex systems and can easily capture complex material and information flows. However, in the context of this study, its use is mainly suggested for future state VSM once we already have a better understanding of how the existing system is organised. This approach also allows the evaluation of different control architectures, such as hierarchical and heterarchical (Frayret et al., 2004), in which different I4.0 scenarios such as order-controlled production, adaptable factories, and self-organising adaptive logistics relies on (Anderl et al., 2016).

Fig. 5b presents two hybrid strategies that can be used to implement VSM models at any of the four levels, which combine discrete-event and agent-based models, where agents behave and interact using mainly statecharts, events, variables, parameters, and functions. First, each passive entity in the DES model is associated with a product agent to capture individual dynamics that can change the process flow. In this case, each agent points to an entity created in the DES model. When an entity is discharged, the agent linked to it is also deleted from the model. Second, each server station is represented by a resource agent that can capture equipment and process complex behaviours more easily. A resource agent controls the exit of entities from a queue by unblocking the hold object. It can also remove entities from the queue or transfer entities from a flow chart to a statechart and vice versa (Borshchev, 2013).

Fig. 5c shows an example of a simplified DES model for a VSM, represented as a process flowchart. Currently, it is the foremost approach adopted in literature to simulate VSM (Uriarte et al., 2020). In this study's context, sole DES models are mainly used to simulate current state VSM at a process or single plant level, depending on the system under analysis. They can also be added inside agents to represent a particular process or the whole process of one or more facilities while analysing the VSM at multiple plants or across companies levels.

The selection of each strategy will depend on the system under analysis, components complexity, variables of interest, and the type of experiment. In order to provide further insights on the application of the modelling strategies mentioned above to the context of I4.0, some key examples identified in the literature are outlined below.

Examples of studies related to VSM at a process and single factory level that uses only ABMS include Ma et al. (2019), Li et al. (2017), and Schönemann et al. (2015). Ma et al. (2019) evaluated the flexibility of a hierarchical with a heterarchical manufacturing system, observing the response of the system to unforeseen disruptions related to production job shop scheduling. They adopted a free market architecture as a negotiation mechanism, an extension of the Contract Net Protocol (CNP) with cost factor adaptation. Li

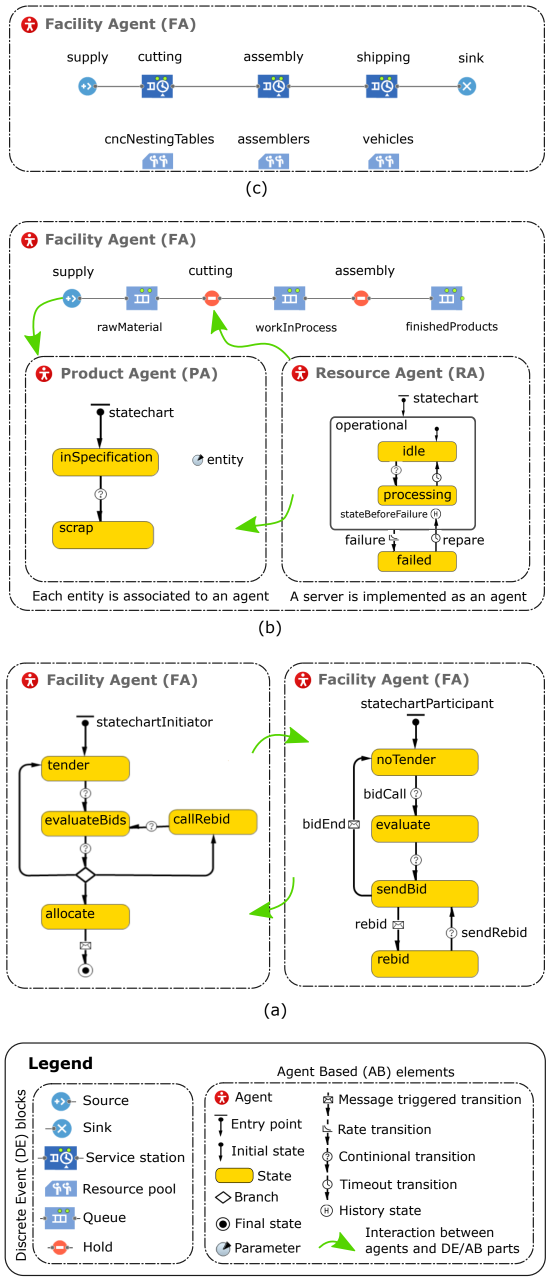


Figure 5: Strategies for implementing simulation-based VSM. (a) sole ABMS. (b) DES interacting with agent-based model. (c) sole DES or DES inside agents.

et al. (2017) proposed a self-organised manufacturing system framework with big data feedback assistance to reduce load-unbalancing in manufacturing scheduling and achieve agility and flexibility. They implemented smart products through RFID tags and proposed an intelligent negotiation mechanism, which is also based on the CNP, focussing on the agents' performance to allocate the tasks. Schönemann et al. (2015) proposed a matrix-structured manufacturing systems framework for agile systems configuration, tested through an agent-based simulation model.

In the same context, an example of studies that use an HS approach (as presented in Fig. 5b) can be found in Nagadi et al. (2018), which proposed a framework to support the design of smart manufacturing systems linked to an IoT architecture that adopts ABMS to capture the behaviour of machines and a DES model to mimic the process flow.

Examples of studies that relate to the VSM model at multiple plants and across companies levels include Xu et al. (2021) and Kádár et al. (2018). Xu et al. (2021) proposed an HS approach to analyse 3D printing technologies adoption to manufacture spare parts for maintenance operations and its impact on operational performance, considering 3D printing facilities located in different network configurations (centralised, decentralised, hub). Their model uses agents to model facilities (top layer), discrete-event elements to model facilities' internal processes (middle layer), and sub-agents to model resources (bottom-up layer), which combines the strategies shown in Fig. 5b and Fig. 5c. Kádár et al. (2018) proposed a distributed collaboration framework to help the cooperation of various production sites, using ABMS to simulate resource sharing in federated production networks that can dynamically re-configure.

5. Proof-of-Concept case

To test the proposed framework, a real case was developed in partnership with a college centre for technology transfer (CCTT) that supports manufacturing SMEs in Quebec in their transition toward I4.0. The proof-of-concept case was conducted in one of the SMEs assisted by the CCTT from the furniture and related product manufacturing sector, NAICS code 337 according to the North American Industry Classification System (NAICS), during 8 weeks. The company produces cabinets for the residential, renovation, and commercial sectors, following a make-to-order or engineering-to-order strategy to accommodate customer preferences and is engaged in the transition to I4.0. The company's identity is protected, and some simplifications were made in the representation of the production processes for the purpose of this article and for maintaining data confidentiality.

5.1. Current state VSM

Following the procedure in Fig. 2, the first step was to design the current state VSM presented in Fig. 6. This VSM focusses on the company's main product family (kitchen cabinets) composed of four types of modules, referred to as modules A, B, C, and D. Customer demand represents 190 modules per day, of which about 11% are modules A, 11% modules B, 67% modules C, and 11% module D. The production process is similar for all modules but with different processing times.

As shown in Fig. 6, the material flow starts with the primary supplied material (melamine panels) being directed to the cutting process, equipped with an overhead crane and two CNC nesting (cutting) tables. Next, the melamine pieces that will compose the modules are identified with a barcode and handled to the wood dowel pins and edge banding processes. Then, they are stocked until all melamine pieces required to assemble a module become available to be

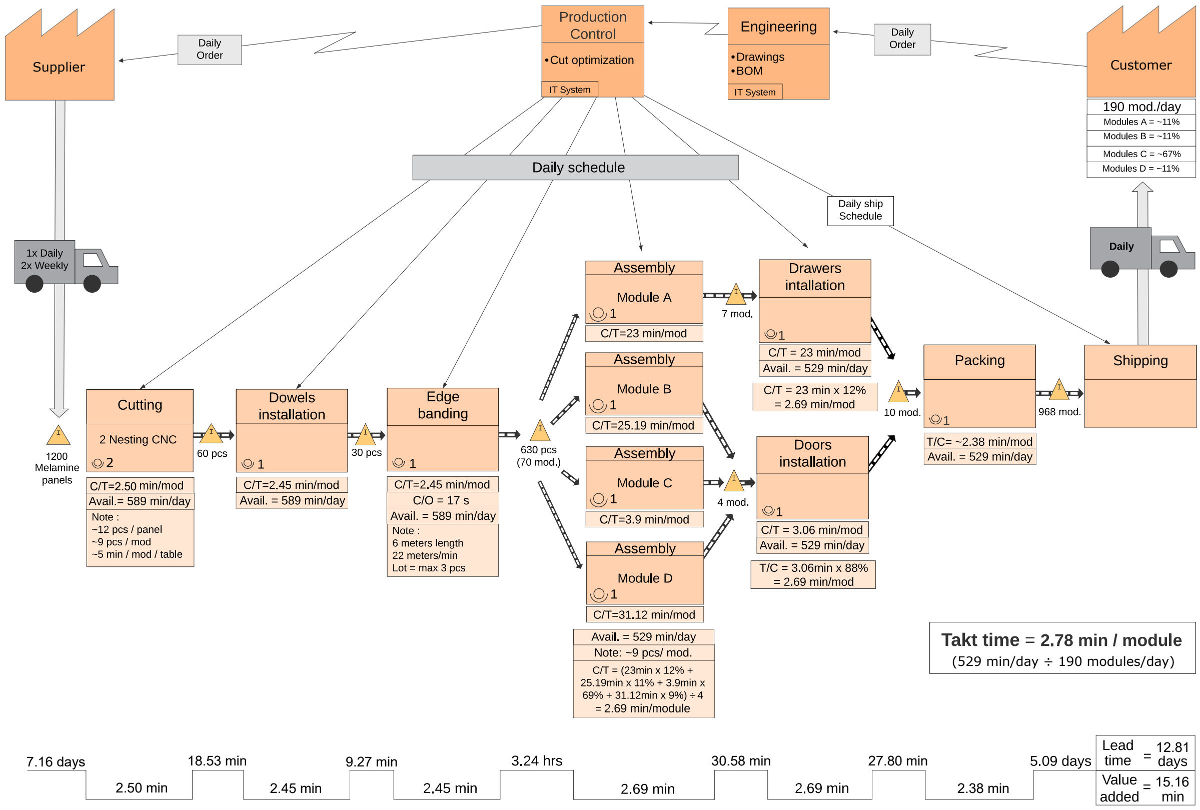


Figure 6: Current state map

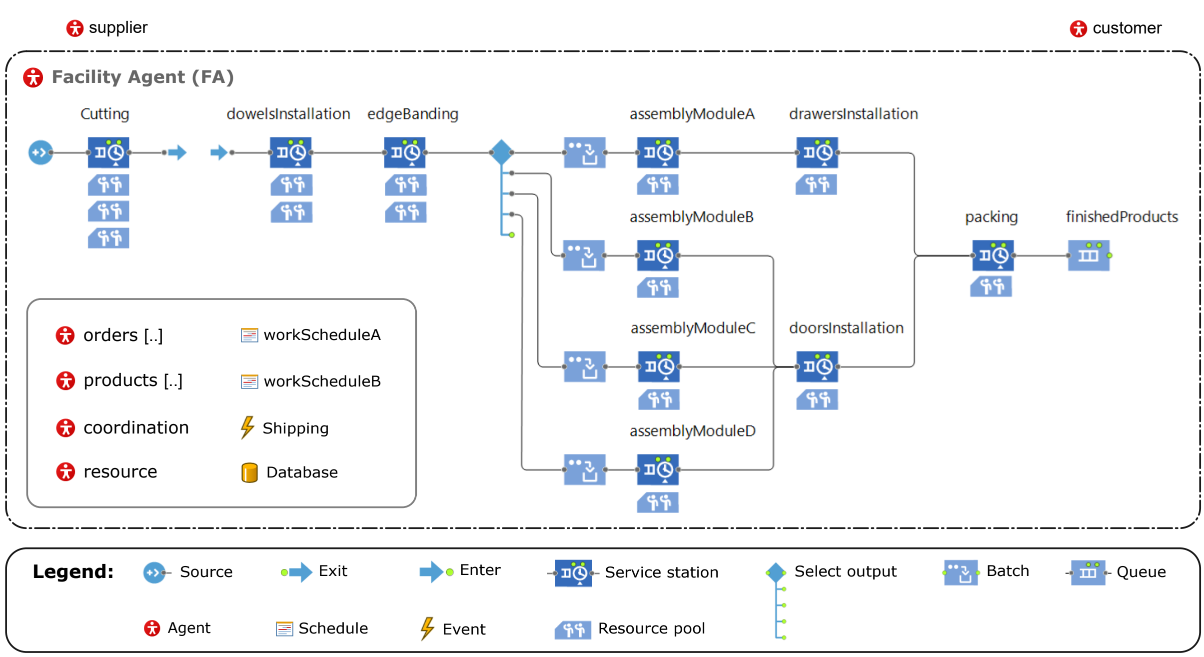


Figure 7: Simulation model of the current state map

manually batched and forwarded to an assembly cell. After that, modules type A go to drawers installation and modules types B, C, and D to doors installation processes. Lastly, the modules are packed and wrapped to avoid any damage during storage or shipping.

The information flow, as depicted in Fig. 6, starts with receiving orders from customers. Next, the engineering department translates customer requirements into technical drawings and creates the bill of materials (BOM). Then, purchase orders are sent to suppliers, and the list of cuts is optimised to minimise material waste during the cutting process. Later, production orders are released to the shop floor for execution.

After analysing the current state map displayed in Fig. 6 together with the company's domain expert for waste identification, the following non-value-added activities were observed: (1) high inventory levels of raw material, work in process (WIP), and finished products, compared to workflow, output and demand. Even though the company adopts the make-to-order or engineering-to-order strategy to treat the orders and purchase raw material, the production process operates following a push production approach, accumulating inventory between processes; (2) the cutting process regulates the overall production and represents the actual bottleneck. The fact that the cutting process, dowels installation and edge banding starts before assembly and operates one to two hours overtime every day corroborates this conclusion; (3) excessive material handling, which is one of the main causes of scrap and rework.

5.2. Simulation model of the current state VSM

The simulation models presented in this study (for both current and future state VSM) were implemented in the Java-based AnyLogic® software (version 8.7.7), one of the main multi-method general-purpose commercial simulation modelling tools available on the market (Scheidegger et al., 2018). Experiments were performed on a 9th generation Intel Core i7-9750H laptop with 32 GB of RAM running the Windows 10 operating system.

To better analyse the current state VSM, a stochastic DES model was developed (see Fig. 7) following the basic agents described in Section 4.1 and the implementation strategy shown in Fig. 5c, presented in Section 4.2. The service stations, resource pools and other discrete-event elements in Fig. 7 represents specialised resource agents, and customers and suppliers agents extend from facility agents. The simulation models of the current and future state VSM consider supply chain uncertainty sources (i.e. demand, supplier delivery lead time, distribution logistics) and internal uncertainty sources (i.e. setup time, machine maintenance and cycle time), which are some of the main uncertainty sources in a value stream (Luz et al., 2021).

The simulation model was validated by comparing the model results to historical data of the existing system, operational graphics, i.e. the dynamical behaviours analysis of performance indicators such as inventory levels and production rate and face validation, where stakeholders (e.g., domain experts) make subjective judgments about the model's sufficient accuracy (Sargent, 2013).

5.3. Future state VSM

The future state map was developed iteratively together with the company's domain experts. The first version followed the system configuration of the I4.0 initiative presented to the CCTT for technical assistance. Essentially, the changes proposed were: (1) replace the edge banding machines with a more modern one; (2) implement an automated storage and retrieval system (AS/RS) in the form of a carousel with a robotic arm for managing inventory before assembly processes, with a storage capacity of about 2000 parts. It would follow a similar solution to the one presented in Crossmuller (2017); (3) automate the assembly of modules type C, adding a pre-assembly process for preparation and removing the protective film from melamine pieces.

After analysing this future state map and the respective simulation model results, we verified that their initial solution did not match demand. Even after some changes to adjust production capacity, keeping the same concept, no significant improvement in the company operational performance was perceived. It became clear that WIP inventory levels would increase, as would the overall production lead time. Therefore, it was suggested to the company that Lean practices and I4.0 principles and technologies should be considered more carefully before going further with the I4.0 initiative. After four iterations, we selected a future state map seen as promising for further analysis as presented in Fig. 8.

The changes incorporated in Fig. 8 include: (1) install a third CNC nesting table to reduce cutting processing time, allowing batching of the melamine pieces into modules for sequencing in a continuous flow, which prevents the need to accumulate work in process before assembly process; (2) place a linear rack with two robotic arms for storage and sequencing the melamine parts in modules for the subsequent processes; (3) replace the edge machine; (4) install a conveyor system connecting all processes to reduce manual handling that can lead to quality defects; (5) adopt a finished goods inventory policy of a maximum of 3 days of coverage.

These changes comply with the company budget for developing the I4.0 initiative envisioning (in the medium to long term) the I4.0 scenarios of order-controlled production and adaptable factory (Anderl et al., 2016) as the company progresses in its maturity and digital capabilities. It explores I4.0 design principles of product personalisation, optimisation, flexibility, agility, and smart factory (de Paula Ferreira et al., 2020), mainly through modelling and simulation, business and industrial automation technologies applied to process engineering manufacturing, production planning and control, and scheduling management areas to improve key performance indicators, i.e. cycle time, inventory levels, lead time, and information sharing. It also pursues the Lean principles of creating a continuous flow and reducing non-adding-value activities. It is important to highlight that modelling and simulation was crucial to generate the insights that led to the proposed VSM that contributed to the company reevaluating and improving their project for an I4.0 initiative.

The future state VSM encompasses several other aspects of I4.0 such as machine-to-machine communication, real-time VSM monitoring, optimisation, flexible systems and machines that are capable of quickly adapting to disruptions (e.g., demand fluctuations, change in orders, quality problems, shortage of raw materials) in a flexible continuous flow, enabling fast decision-making processes (e.g. adjust takt time, rescheduling production orders).

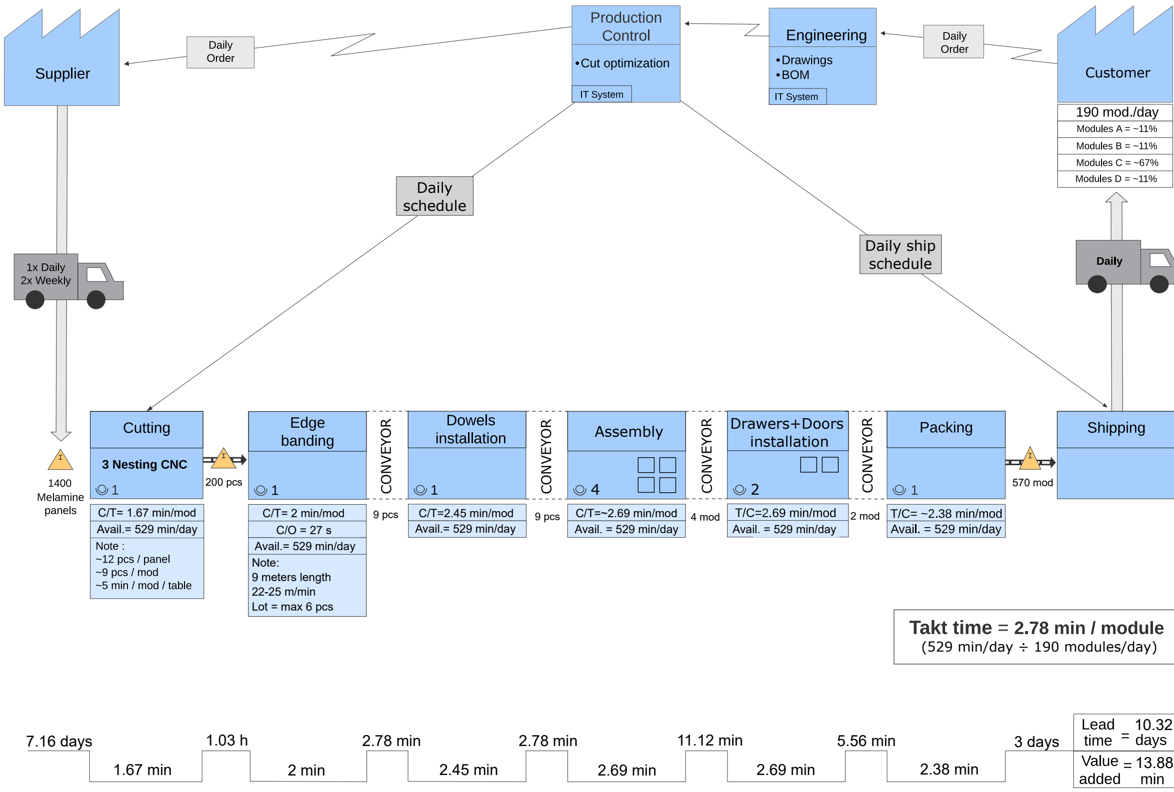


Figure 8: Future state map

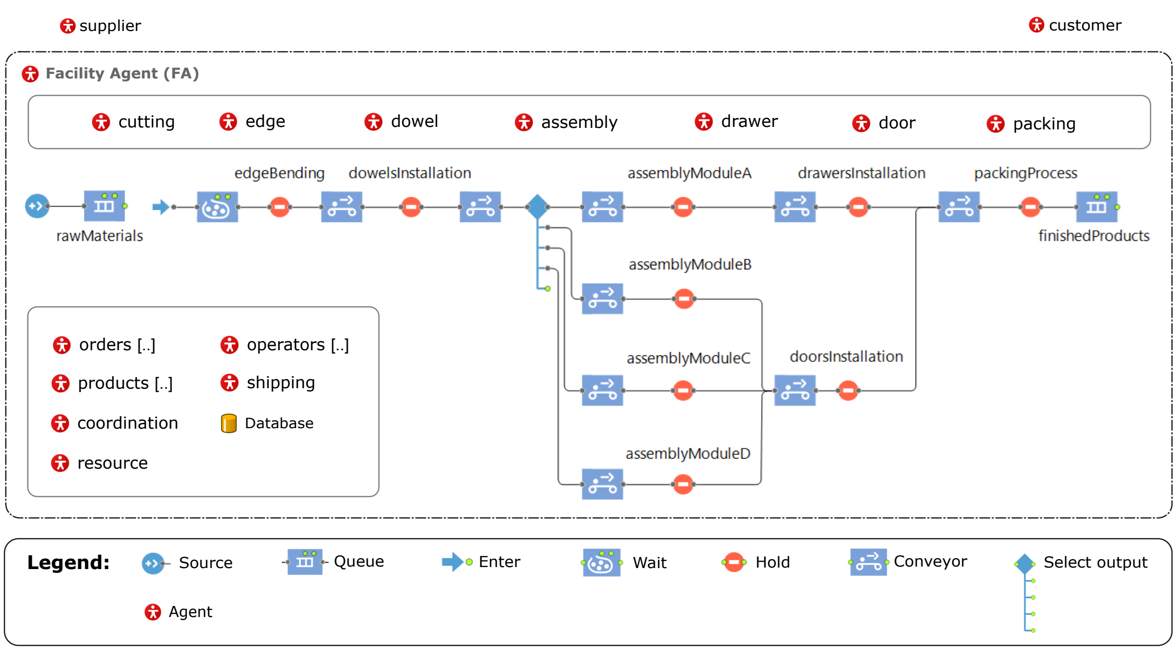


Figure 9: Simulation model of the future state map

5.4. Simulation model of the future state VSM

To analyse the future state VSM, an HS (DES + ABMS) model was developed (see Fig. 9) following the basic agents proposed in Section 4.1, with the specialisation of the resource agents as presented in Fig. 10, which encapsulates the functions of Lean VSM icons and other functions (e.g., self-regulation) to represent the I4.0 scenario analysed. The implementation of the model followed the strategy shown in Fig. 5b, described in Section 4.2., where a resource agent represents each server station to capture equipment and process complex behaviours and interactions easily, mainly through statecharts, functions and message passing. The HS

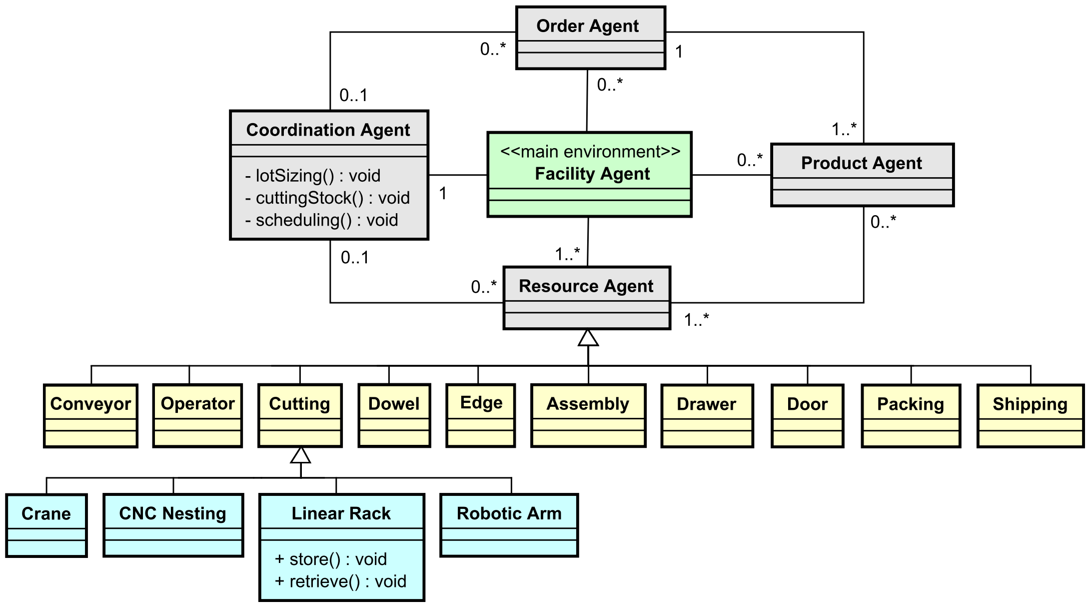


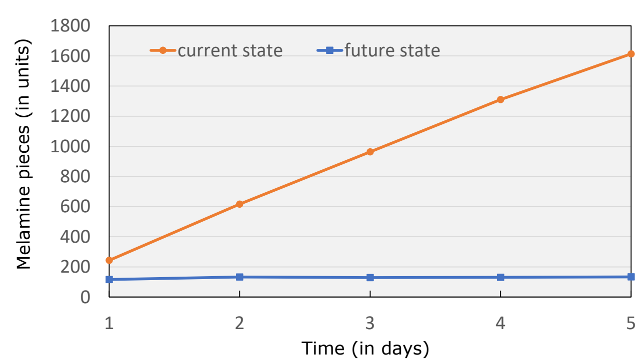
Figure 10: Basic and specialised agents in the simulation model

model was validated by a field expert with knowledge about the system being modelled and simulated (i.e. face validation) and by performing sensitivity analysis, degenerated tests, and extreme condition tests (Sargent, 2013).

5.5. Results

The work-in-process (WIP) inventory levels were one of the main concerns to the company for different reasons (limited space, quality problems, insurance policy). As can be seen in Fig. 11, the simulation results show that the WIP levels of the future state VSM are significantly lower compared with the current state VSM. It is mainly possible because, in the future state, we assume that the melamine panels are sequenced to maximise modules formation when cut, and the melamine pieces are batched and sequenced directly after the cutting process. Therefore, in case of unexpected or unplanned events, such as a customer that changes the delivery day after production has started or a part is scrapped and there is no raw material in stock for replacement, the WIP is minimised since we can reschedule the cutting process more flexibly and rapidly before most melamine panels for an order have been cut. It also reduce the inventory of finished products by improving production planning and control, avoiding anticipating production orders, respecting customers delivery dates.

As shown in Fig. 12, the third nesting table in the future state VSM reduces the mean waiting time to form a module below the takt time. It removes the bottleneck from the cutting process while operating the production in a continuous flow, respecting the cutting stock optimisation model adopted by the company to minimise material waste, where usually two or more melamine panels need to be cut before the pieces needed to form a module become available to the subsequent process. The HS-VSM enabled capturing the behaviour of the more complex entities (e.g., cutting process, edge process) and of the system under disruptions (e.g., turbulent demand, change in orders, quality problems) to minimise inventory levels and maximise fillrate.



Note: the 95% confidence interval contains zero, indicating no statistically significant difference between the means.

Figure 11: Mean work-in-process

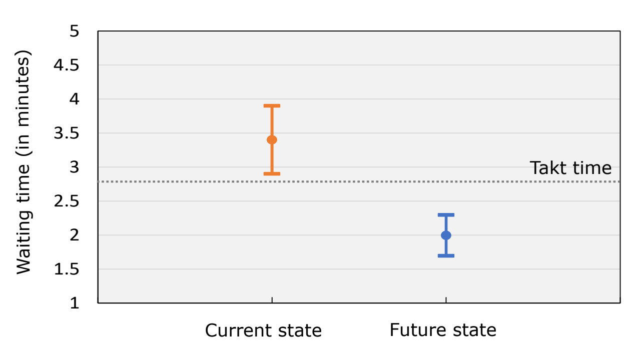


Figure 12: Mean waiting time for having the melamine pieces forming a module after cutting with 95% confidence interval

Table 4
Summary of the results

Performance metric	Unit	Current state	Future state
Value added time (VAT)	min	15.16±0.2	14.21 ±0.3
Production lead time (LT)	days	12.81 ±0.3	10.32 ±0.1
Production output per day	mod.	190 ± 5	190 ± 2

Note: Means with 95% confidence intervals.

As presented in Table 4, the production lead time (LT) in the future state is reduced around 19%, which reinforce the potential benefits of the I4.0 initiative. Nevertheless, comparing the value-added time (VAT) with LT can be quite shocking, as highlighted in Rother and Shook (2003). The results in Table 4 indicates that the processing time for producing a module will be around 14.21 min, whereas that module will take around 10.32 days to make its way through the production plant until it reaches the customer, suggesting there is lots of room for improvement.

5.6. Discussion

The proof-of-concept case illustrated how the proposed framework can be applied to build hybrid simulation-based value stream maps and how they may be used to support I4.0 initiatives in manufacturing SMEs.

The application of the overall approach lasted for 8 weeks, which fitted the decision time window of the company under analysis. It is worth mentioning that this study was developed in the middle of the COVID-19 pandemic and involved a single modelling and simulation analyst, having influenced the developing time significantly, especially for data collection. Overall, the modelling and simulation efforts based on the I4.0 scenarios selected for analysis and the number of iterations required to design the future state VSM that may also imply simulation model redesign are the main determinants of the developing time.

The fact that Lean VSM is a widespread practice in the industry, as reported in Shou et al. (2017) and Uriarte et al. (2020), helped bring familiarity and engage stakeholders (e.g. managers, IT analysts, operators) in the development of the I4.0 initiative, and may help reduce the learning curve for its application (Glock et al., 2019). Moreover, the use of VSM linked with I4.0 principles facilitated interactions with the company for data collection, modelling, and simulation. Furthermore, it helped the company better understand the I4.0 concept and rethink their I4.0 initiative, putting it into a broader perspective, considering I4.0 scenarios. In the beginning, the company focussed mainly on increasing automation levels in a way that hardware determines the structure and functions are tied to hardware (i.e., Industry 3.0) instead of flexible systems and machines (i.e., I4.0), where functions are distributed through the network, which can cross company boundaries and products can be part of the network (DIN SPEC 9134, 2016). It is a common misconception of I4.0 that may be explained by the lack of a common understanding about I4.0, as discussed in de Paula Ferreira et al. (2020). Moreover, when LM principles and practices are not implemented before bringing in technologies and digital innovation related to I4.0, there is also the risk that "the results would be just a digitalisation of existing wastes" (Ciano et al., 2021, p. 1339). If applied to efficient operations, automation technologies may amplify efficiency, but they may amplify inefficiency if applied to inefficient operations (Buer et al., 2018).

Many of the insights obtained from this study, partially reflected in the future state VSM, would not be possible without modelling and simulation, as identifying the cutting process as the bottleneck, since it was not evident for any of the participants. It became evident only when we started to think about establishing a continuous flow. This result is in accordance with Vanzela et al. (2017), which indicate that the cutting sector represents the bottleneck of most furniture plants. The use of modelling and simulation served not just to refine the VSM and confirm the benefits envisioned in the future state map but also to enrich participation, helping in the reasoning on the potential impacts of the I4.0 initiative on their processes and benefits to operational performance. The use of modelling and simulation complemented the VSM analysis. It supported the analysis that showed that the company's initial project proposal neither matched the demand nor complied with I4.0 principles. Even with certain adjustments, it would not improve the operational performance of the company considerably, reducing their flexibility, agility, and increasing their inventory levels and lead time, having practical implications in the I4.0 initiative, since it was performed before commissioning and contributed to the project that is being implemented.

To the best of the authors' knowledge, this is the first study to propose a general framework to model and simulate VSM in its different levels applied to the context of I4.0 using HS (DES + ABMS). Previous studies integrating Lean VSM with simulation modelling focus mainly on DES or SD (Uriarte et al., 2020), which are unable to capture I4.0 design principles comprehensively as ABMS or HS (de Paula Ferreira et al., 2020). Moreover, they do not address I4.0 context nor provide a comprehensive framework (Lugert et al., 2018; Uriarte et al., 2020). Furthermore, previous approaches do not enable representing I4.0 components, being able to cover a limited number of I4.0 production scenarios since they do not match important I4.0 requirements, e.g. autonomy, proactivity, learning capacity, reconfigurability, and social ability (de Paula Ferreira et al., 2020). In addition, they do not explore the use of Lean VSM with HS to support I4.0 initiatives in manufacturing SMEs, where most "SME oriented tools, frameworks and models do not extend beyond giving a current I4.0 readiness state of an organisation" (Masood and Sonntag, 2020, p. 3). Hence, this study may contribute to facilitating the future adoption of I4.0 principles (e.g. flexibility, agility, decentralisation, virtualisation) and technologies (e.g. the Internet of Things, Cobots, Autonomous Mobile Robots) by enabling manufacturing SMEs to identify improvement and process innovation opportunities and analyse changes in materials, equipment, processes, and information flows associated with I4.0 application scenarios.

It is mainly possible thanks to the integration of ABMS into the HS-VSM since "software agents are particularly suitable for representing I4.0 components and enabling I4.0 interactions" (Fay et al., 2019, p. 1).

6. Conclusions and future research directions

The mutual relationship of Lean Manufacturing (LM) and Industry 4.0 (I4.0) is of growing interest and importance both from an academic and a practitioner perspective. LM is seen as prerequisite to implementing I4.0. This study investigated the extensibility of Lean practice Value Stream Mapping (VSM) to support I4.0 initiatives in small and mid-size enterprises (SMEs), developed in collaboration with a Canadian college centre for technology transfer (CCTT).

It proposes a comprehensive framework to model and simulate VSM at its different magnification levels (i.e. process, single plant, multiple plants, across companies) applied to the context of I4.0 using a hybrid modelling approach that combines discrete event and agent-based modelling and simulation. This approach can capture I4.0 design principles and enable Lean VSM to analyse I4.0 production scenarios comprehensively since it matches I4.0 requirements. The proposed framework was successfully tested in an industrial case developed in a manufacturing SME from the furniture and related product manufacturing sector, investing 3-5 million dollars in I4.0. It helped support the company's I4.0 initiative by establishing improved modes of operation and enabling the analysis of changes in materials, equipment, processes, and information flows associated with I4.0 application scenarios during the conception and planning stages of the project, identify system requirements for technical specifications, interact with suppliers, and achieve a common understanding between stakeholders.

This study has some limitations. First, the study's scope was limited to SMEs in the manufacturing sector, and the industrial case focussed on VSM at the single plant level. However, example cases of the configuration of the basic agents for VSM at multiple plants and across-companies level were provided. Second, applying the proposed approach can be seen as time-consuming and expensive depending on a company's decision-making time window and the levels of investment available for developing an Industry 4.0 initiative since a modelling and simulation analyst has to be involved. Nevertheless, these issues can be remedied by applying the proposed approach through an intermediary organisation whose purpose is to support companies' transition to Industry 4.0 (e.g. CCTT), ensuring that there is enough time for the model results to be useful and that its application cost does not exceed possible savings.

Further research is required to fully explore the potential applications of the proposed framework, including more complex cases. Future research is also needed to examine its generality and validity to other industrial sectors and VSM levels. In addition, the incorporation of artificial intelligence techniques, e.g. applying machine-learning models to process input data for the simulation model or to represent the behaviour of Industry 4.0 components in the simulated system, can be explored in future works using the same simulation platform. Moreover, the proposed approach in this study may serve as a basis for developing a software library (build-in blocks) for VSM in the multi-method simulation modelling software AnyLogic®. The application of other software tools can also be investigated.

Acknowledgement

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