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A framework for identifying and analysing industry 4.0 scenarios

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ABSTRACT

Industry 4.0 is a central strategy to strengthen the competitiveness of the manufacturing sector over the next years. Nevertheless, there is a lack of common understanding of Industry 4.0 and tools to help companies' transformation to Industry 4.0, especially for small and medium-sized enterprises (SMEs). To address these research gaps, this study proposes a framework to characterise and evaluate Industry 4.0 scenarios to aid companies' transition towards Industry 4.0. For this, a design science (multi-methodological) approach is adopted, including an Industry 4.0 use case survey, modelling and simulation and two proof-of-concept cases developed in collaboration with a Canadian college centre for technology transfer. The results indicate that the proposed framework can help companies identify Industry 4.0 scenarios more intuitively to assist project conception, portfolio selection and planning during Industry 4.0 roadmap development. Finally, the results of this study suggest that Industry 4.0 can be implemented incrementally while companies increase their digital capabilities and maturity.

1. Introduction

Industry 4.0 (I4.0) is considered the main strategy to strengthen the competitiveness of the manufacturing sector over the next years [1, 2]. It refers to "a collective term for technologies and concepts of value chain organisation" [3, p. 11], having implications for value creation, organisational performance, development of new business models, services and work organisation [1, 2]. The I4.0 was triggered by the need to shorten development and innovation cycles, individualisation of demand, and resource efficiency, and is driven by significant advancements and access to information, communication and automation technologies, such as the internet of things (IoT), big data, artificial intelligence, collaborative robots, and simulation [2, 4, 5, 6].

Despite its increasing relevance, there is still a lack of shared understanding of I4.0 [7], and it is not yet well-established in practice, making it difficult for companies to plan I4.0 implementation effectively. Furthermore, there is still a lack of research about the risks, costs, revenue potential, implementation barriers, and tools to help companies' transition towards I4.0 [8, 9, 10, 11, 12]. Especially for small and medium-sized enterprises (SMEs) that have different priorities and face different challenges to adopt I4.0 compared to large companies [13]. As revealed by Moeuf et al. [14, p. 1132], "despite the growing number of new tools and technologies, most of them are under-exploited, if not ignored by SMEs", which can prevent SMEs from remaining competitive in the digital global economy. There is a need to help SMEs to identify areas of their business that could be positively impacted by I4.0 technologies and how they should be implemented to improve their performance [13].

To reduce this research gap, this study aims to investigate the building blocks to implement I4.0 and propose a framework to characterise and evaluate I4.0 scenarios for application in a more practice-oriented manner to help clarify the understanding of the I4.0 concept and support companies' transition towards I4.0. For this, a design science (multi-methodological) approach is adopted, including a review of Industry 4.0 cases, modelling and simulation and proof-of-concept cases. This study's scope is limited to manufacturing industries, focussing on SMEs, the technological dimension of I4.0 and production scenarios, which is one of the main focuses of I4.0 [15].

The contributions of this study are twofold. First, it proposes a procedural/prescriptive framework for identifying and analysing I4.0 scenarios for application more intuitively to support the adoption of I4.0 related technologies by manufacturing companies, addressing part of the research gap/opportunity pointed out in different studies for the realisation of I4.0 [8, 9, 12, 16, 17, 13]. In this sense, to clarify and exemplify what I4.0 scenarios are, this study reviews several application examples of I4.0 reported in the literature, which helps elucidate the fuzziness of understanding about the term I4.0. Second, it presents a framework that incorporates modelling and simulation as a supporting tool for projects conception, portfolio selection and planning during I4.0 roadmap development, which is still under-explored in the literature [18, 19, 20]. This study presents two proof-of-concept cases developed in a Canadian college centre for technology transfer (CCTT) and an SME from the furniture

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and related product manufacturing sector to test the overall proposed approach.

The remainder of this paper is organised as follows. Section 2 presents the research background. Section 3 describes the research methodology. Section 4 presents the proposed framework. Section 5 presents the proof-of-concept cases developed in collaboration with a CCTT. Section 6 presents the discussion. Finally, conclusions, limitations and opportunities for future research are outlined in Section 7.

2. Background

There are several successful example cases of applying I4.0 principles and technologies reported in the literature that brings to light the potential benefits of adopting I4.0 [21, 22, 23, 24]. Nevertheless, it is worth mentioning that implementing I4.0 in companies is generally a complex and resource-demanding process, from the financial and organisational perspectives, involving significant changes in infrastructure, processes, operations, work organisation, skill requirements, and business models [25, 10, 13, 17, 23, 26, 24]. Moreover, "there is no one-size-fits-all solution for companies" seeking to implement I4.0 [27, p. 56]. In light of that, we reviewed the literature on I4.0 implementation, identifying the essential practice building blocks to support the realisation of I4.0, introduced in the subsections below.

2.1. Maturity model

The I4.0 maturity model (also referred to as readiness assessment model) is an artifact used to evaluate the degree of readiness of an organisation to adopt/implement the I4.0 strategy and/or evaluate the maturing state of an organisation in its journey towards I4.0 [27, 28, 11]. The assessment of readiness and maturity is considered the first step for implementing I4.0 [11], which can be performed through a company's self-assessment or collaborative assessment with the help of a consulting firm [28, 29].

There are over 13 different I4.0 maturity and/or readiness models available in literature [30, 11], of which the ones proposed in [28], [31] and [27] are among the three most cited ones. They are composed of maturity dimensions, maturity measurement items, and maturity score levels [11]. As an example, the maturity model proposed in [28] is composed of a total of 38 items, divided into 9 dimensions of I4.0 (i.e. strategy, technology, operations, leadership, customers, products, culture, people, governance), and classify a company's degree of I4.0 implementation into 5 levels.

Here we present the formulations that synthesises these maturity models. Overall, each of these maturity models can be mathematically represented by a set of maturity measurement items $I = \{1, ..., n\}$ divided into partitions P_d representing $d \in D = \{1, ..., r\}$ dimensions of I4.0. An organization's maturity score levels can be calculated into three steps based on a closed-ended structured survey conducted with a group $E = \{1, ..., e\}$ of industry experts. First, the importance weight g_{di} of each maturity item $i \in S_d$ is defined based on the average of the ratings x_{die} from all experts $e \in E$ recorded on a four-point Likert scale (1 = not important and 4 = very important) using Equation 1.

$$g_{di} = \frac{1}{|E|} \sum_{e \in E} x_{die} \qquad \forall\ d \in D,\ i \in P_d \tag{1}$$

Second, the maturity level for each measurement item l_{di} is calculated based on the average of the score y_{die} attributed for all experts $e \in E$ for each item $i \in P_d$ recorded on a five-point Likert scale (0 = not implemented and 5 = fully implemented), assuming equal weight for all respondents, using Equation 2.

$$l_{di} = \frac{1}{|E|} \sum_{e \in E} y_{die} \qquad \forall\ d \in D,\ i \in P_d \tag{2}$$

Third, the maturity level for each I4.0 maturity item m_{di} is calculated using the weighted average in Equation 3.

$$m_{di} = \frac{l_{di} \times g_{di}}{g_{di}} \qquad \forall\ d \in D,\ i \in P_d \tag{3}$$

Additionally, the maturity score level for each I4.0 maturity dimension m_d and the overall maturity score m can be computed by the weighted average in Equation 4 and 5 respectively.

$$m_d = \frac{\sum_{i \in P_d} (l_{di} \times g_{di})}{\sum_{i \in P_d} g_{di}} \qquad \forall\ d \in D \tag{4}$$

$$m = \frac{\sum_{d \in D} \sum_{i \in P_d} (l_{di} \times g_{di})}{\sum_{d \in D} \sum_{i \in P_d} g_{di}} \tag{5}$$

It is important to mention that the I4.0 roadmap proposed in [32] includes a maturity gap analysis, where not just the as-it-is state but target-state for each maturity item needs to be defined and analysed to prioritise development items for I4.0 projects realisation in companies.

2.2. Roadmap

The I4.0 roadmaps (also referred to as process models or procedure models) enable organisations to establish a detailed set of guidelines on the steps to take for achieving higher I4.0 maturity levels more effectively [20]. It is a tool for multidisciplinary teams to define a "chronological sequence of the planned measures in the form of concrete project" [18, p. 196] considering short, medium, and long-term strategies to foster the implementation of I4.0 [19].

There are more than ten I4.0 roadmaps available in the literature [33, 18, 34, 19, 32, 20, 26], which are composed of different phases (e.g. analysis, objective, implementation) and different project management and creativity techniques, such as brainstorming, SWOT (strengths, weaknesses, opportunities, and threats) analysis, business model canvas, balanced scorecard, and cost-benefit analysis [20, 18].

As an example, Beaudoin et al. [33] proposed an I4.0 roadmap for SMEs based on six steps: 1 - define a transition strategy (process, product, services); 2 - select one or more activities that can be improved through an I4.0 project; 3 - define the scope for an I4.0 project (monitoring, control, optimisation, autonomy); 4 - choose the I4.0 technologies and techniques to be deployed; 5 - implement the I4.0 project; 6 - Assess the gains of the I4.0 project and launch the next I4.0 initiative. This process is repeated until companies reach the desired I4.0 maturity level. The authors also highlight the essential role of leadership, project management, and technical competencies to ensure a company's successful transition toward I4.0.

The majority of these I4.0 roadmaps follow a project portfolio management (PPM) approach that refers to "the continuous process of selecting and managing the optimum set of project-oriented initiatives that deliver the maximum in business value or return on investment" [35, p. 1]. PPM problems can be addressed through different methods, such as comparative, scoring, optimization, and simulation methods, the latter being the least explored in literature [36]. Moreover, modelling and simulation can be used as supporting tools to evaluate and gain insights about I4.0 scenarios before implementation [16, 37], which remain underexplored in the I4.0 roadmap literature [18, 20].

2.2.1. *Industry 4.0 scenarios*

A fundamental activity in developing an I4.0 roadmap is defining applicable I4.0 scenarios for realisation. An I4.0 scenario refers to a project or practice that reflects one or more design principles and enabling technologies characterising the I4.0 [3, 34, 8, 19, 20]. It serves as a conceptual model for practical applications, that is, for developing an I4.0 use case in a company, that can later become a showcase for other areas or for other companies if successful [20].

The first studies to propose a conceptual model to support the identification of I4.0 scenarios for implementation in companies are [3] and [34]. These studies conducted a systematic literature review and meta-analysis to identify the main design principles and enabling technologies of I4.0, arguing that those I4.0 components may be used to identify, describe, and select I4.0 scenarios for further investigation [3, 34]. It is worth mentioning that the list of I4.0 principles and technologies has been updated in [19] and [16].

Another model for I4.0 scenarios is proposed in Anderl et al. [38], which follows a use case approach, focussing on manufacturing companies' value-added processes. They classify the I4.0 application scenarios into seven categories: order-controlled production; adaptable factory; self-organising adaptive logistics; value-based services; transparency and adaptability of delivered products; operator support in production; smart product development for smart production; innovative product development; and circular economy. It is important to notice that in [38] the authors make a distinction between I4.0 application scenario and I4.0 application example, where the first refers to a generic description of a user's problem and the latter to a particular solution for a user. In summary, I4.0 application scenarios can lead to multiple I4.0 application examples [38]. Similarly, [23] proposed a I4.0 business model pattern framework, identifying 13 patterns of I4.0 business models, which can be used to guide manufacturing companies towards I4.0.

Nevertheless, "further research should challenge their utility by identifying, describing, and selecting Industrie 4.0 scenarios from an academic or practical perspective" [3, p. 13] to guide companies towards I4.0. Moreover, they should be adapted to the context of SMEs.

2.3. Reference architecture

There are different reference architectures related to I4.0 [39, 40], of which the RAMI4.0 (Reference Architecture Model for Industry 4.0) [41], the one adopted in this study, is gaining broad acceptance in academy and industry, helping consolidate the main aspects of I4.0 and provide a blueprint for I4.0 implementation. The RAMI4.0 is built upon existing standards and methods from ICT and production fields, such as ISA-95 (International standard for enterprise control systems integration) and agent technology [15, 39].

The RAMI4.0 is composed of three dimensions: (1) layers: asset, integration, communication, information, functional, business; (2) life cycle & value stream; and (3) hierarchy levels: product, field device, control device, station, work centres, enterprise, connected world [15]. It extends ISA-95 (IEC 62264) hierarchy levels by adding the product level at the bottom and connected world level at the top of the pyramid [15, 40, 39]. Overall, RAMI4.0 combines the "life cycle and value stream with a hierarchically structured approach for the definition of I4.0 components" [15, p. 6], which designates the agents (physical or virtual object) in the system, endowed with communication ability and technical functionality [39]. RAMI4.0 introduces the I4.0 component as the basic element for building I4.0 systems, consisting of an asset plus an administration shell, which refers to an asset's data-warehouse [41].

It is important to highlight that RAMI4.0 is grounded in agent-based and holonic paradigms to modelling manufacturing systems [39].In line with that, modelling and simulation may provide important insights on RAMI4.0 application, besides enabling I4.0 systems management [1].

2.4. Modelling and Simulation

Modelling and simulation is a primary research methodology in the fields of industrial engineering and operations management [42, 43, 44, 45, 46, 47, 48, 49]. It denotes a set of techniques for designing a model (abstract and simplified representation) of a real or hypothetical system for conducting computational experiments with the model in a risk-free environment for proof, explanation, prescription, empirical guidance, among other applications [50, 51].

The state-of-the-art review conducted by de Paula Ferreira et al. [16] describes 10 simulation-based approaches applied to the context of I4.0, of which hybrid simulation (HS) that combines discrete-event simulation (DES) with agent-based modelling and simulation (ABMS) is the focus of this study. It considers that I4.0 components development is rooted in the notion of agent technology [39] and that HS is a primary approach used in the context of I4.0 [16].

HS (ABMS + DES) provides a bottom-up approach to modelling systems [52], where the DES model represents the process flow, and the ABMS is used to substitute DES passive entities for certain active entities, considering individual agents behaviours and autonomy [53, 49, 52]. It considers both an agent perspective and a process perspective to define the model implementation. From Macal et al. [53, p.207], true ABMS in operational research (OR) that focusses on decision support and problem-solving does not exist; combined applications of ABMS with DES "seems to be the way forward to tackle the problems in what becomes more an investigation into behavioural OR due to the recent shift of attention from manufacturing to service industry".

ABMS is a bottom-up, decentralised approach, where agents are modelled and implemented in a computer simulation, and their interactions may produce observable global emergent behaviours [54, 55]. An agent is a complex software unit endowed with attributes and methods [56]. It consists of "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" [57, p. 982]. In a general way, the agent-based simulation (ABS) executes an agent-based model (ABM) of a multi-agent system (MAS) to study the behaviour of certain parameters of the model or environment on interest values. ABMS is a type of application of MAS, both part of agent technology, whose domain of applications is larger than simulation [58].

3. Methodology

Regarding its nature, this research is classified as applied research, whose aim is to generate knowledge for practical applications. From the point of view of how to approach the problem, it adopts mixed methods, combining qualitative and quantitative approaches. From the standpoint of technical procedures, this research follows the Design Science Research (DSR), which is a well-accepted research paradigm in information systems and industrial engineering domains to support the development of new artifacts (e.g. constructs, algorithms, frameworks, implemented and prototype systems) to solve relevant open problems innovatively or more effectively to enhance organizational efficacy [59].

From Hevner et al. [59], the development of an artifact starts with the awareness of the business environment and business needs/problems. The environment (See Fig. 1) characterizes the problem space where the phenomenon of interest framing the research is located, composed of people, organizations, and technologies [59]. Next, possible solutions designed to meet identified needs are derived from the existing knowledge base, composed of foundations and methodologies. After that, the assessment and refinement processes are performed. Nevertheless, the "refinement and reassessment process is typically described in future research directions" [59, p.80]. Lastly, the research results are communicated and codified in the knowledge base.

An overview of the research design is shown in Fig. 1, following [59] and [60] guidelines. It comprises a multi-methodological approach to developing a framework for identifying and analysing I4.0 scenarios to support companies transition towards I4.0. It includes a literature review on I4.0 implementation, an I4.0 use-cases survey, modelling and simulation, and proofs-of-concept.

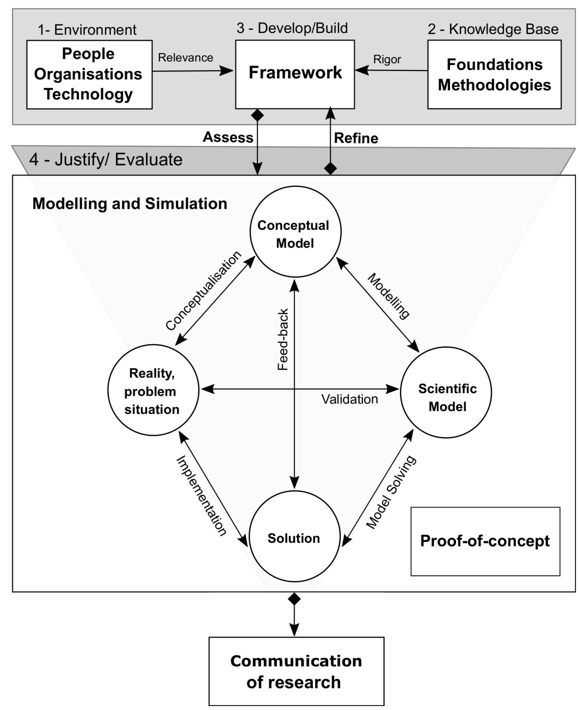


Figure 1: Research design. Adaped from [59] and [60].

This study counts with primary and secondary data collected from a college centre for technology transfer (CCTT) and four manufacturing SMEs assisted by the CCTT, located in the province of Quebec, Canada, engaged in the transition toward I4.0. The CCTT was selected as a research setting since its primary role is to aid manufacturing SMEs' transition toward I4.0, matching this article's research scope. Moreover, the CCTT adopts a living lab and triple helix collaboration approach, which involves academic institutions (i.e. college, university), government, and industry, being supported by an extensive network of manufacturing SMEs. Additionally, several I4.0 use cases were identified through the Web of Science, Scopus, and Google Scholar databases and analysed qualitatively to test the proposed framework and to gain in-depth insights about I4.0 implementation, following a case survey methodology [61].

Specifically, the data collected for the proof-of-concept case include direct observation during participation in CCTT weekly meetings related to I4.0 projects for six months, manufacturing and process data from their living lab, semi-structured interviews, and surveys conducted with industry experts associated with the CCTT that are directly involved in I4.0 research, development, maturity assessment, or technical assistance to guide SMEs towards I4.0. It also includes business process and maturity assessment data from four manufacturing SMEs collected by the CCTT to support the case selection and contextualisation for enabling posterior technological transfer. Moreover, it includes data from a Canadian SME from the furniture and related product manufacturing sector investing in I4.0 to improve their operational performance. Further details on the methodology are provided in the next section.

4. General framework

Fig. 2 presents the general framework to guide the implementation of I4.0 scenarios in manufacturing companies, which combines three essential practice building blocks for the realisation of I4.0 (i.e. maturity model, roadmap, reference architecture) with modelling and simulation.

The first step consists of performing the assessment of a company using an I4.0 maturity model. Then, based on the maturity levels and business strategy, a company can perform a maturity gap analysis, as proposed by [32] to prioritise maturity items for development and define its roadmap to reach higher I4.0 maturity levels, defining I4.0 scenarios for implementation. This phase relates to technology project portfolio management, as discussed by [20]. At this stage, I4.0 scenarios can be identified and selected for evaluation through modelling and simulation to support project conception, project portfolio selection and planning.

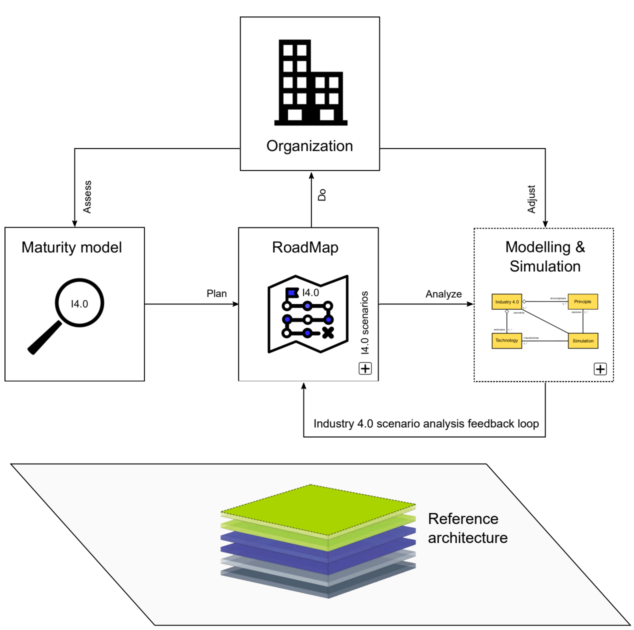


Figure 2: General framework to support manufacturing companies to move towards Industry 4.0

Thereafter, the simulation experiments' results can be feedback to refine the I4.0 roadmap for realisation. Lastly, the results obtained with the implementation of the I4.0 scenario in a company can be feedback for verification, validation, and improvement of the simulation model that can be used later on to support other I4.0 initiatives in the company.

The RAMI4.0 reference architecture relates to the other elements in Fig. 2 in different ways, encompassing the foundation all the other elements are built upon. First, RAMI4.0 gathers the essential aspects of I4.0 and provides a common ground for organisations and multidisciplinary teams on how to approach I4.0 implementation in a structured manner [15, 41]. Moreover, it serves as a basis for developing or refining I4.0 maturity models, as described in [62]. Furthermore, RAMI4.0 can be used to translate I4.0 scenarios identified during the roadmap development from high abstraction levels to engineering requirements for implementation in companies by abstracting and linking I4.0 architectural aspects to proven industry standards, such as IEC62890, IEC 62264, and IEC 61512/ISA 95 [41]. In addition, RAMI4.0 provides recommendations of technologies and guidelines for modelling I4.0 systems encompassing technological and human aspects [15, 39, 63].

The next two subsections present the frameworks to help to identify and analyse I4.0 scenarios for realisation in companies, representing two subprocesses of the general framework as indicated in Fig. 2 by the $\boxed{+}$ symbol, where this study's main contributions reside.

4.1. A framework for identifying I4.0 scenarios

Fig. 3 presents a conceptual framework to help manufacturing companies operationalise the I4.0 concept and identify I4.0 scenarios for realisation more intuitively. It is composed of four blocks of constructs. The first block indicates the design principles of I4.0, adopted from [16]. The second block refers to the enabling technologies of I4.0, compiled from [64] and [65]. The third block relates to the main sub-areas of industrial engineering and operations management, adopted from [43] and [66]. The fourth block presents key performance measures used by manufacturing companies that are associated with the expected benefits of I4.0 [24, 67, 68, 69].

It is important to highlight that each block may include other elements, considering the continuous advancement of I4.0 enabling technologies and practices. Furthermore, there are over 100 metrics (e.g. operational, economic, environmental) available in the literature that can be considered for performance evaluation at the strategic, tactical and operational levels, depending on contextual factors [70, 71, 72, 73, 69, 24].

The process for identifying an I4.0 scenario consists of selecting one or more elements of any of the four blocks in Fig. 3 and connecting it with one or more elements of at least two other remaining blocks and by following a simple gap-filling natural language generation approach. The main template used to generate the I4.0 scenarios is presented in Tab. 1. After that, the I4.0 scenarios can be analysed and

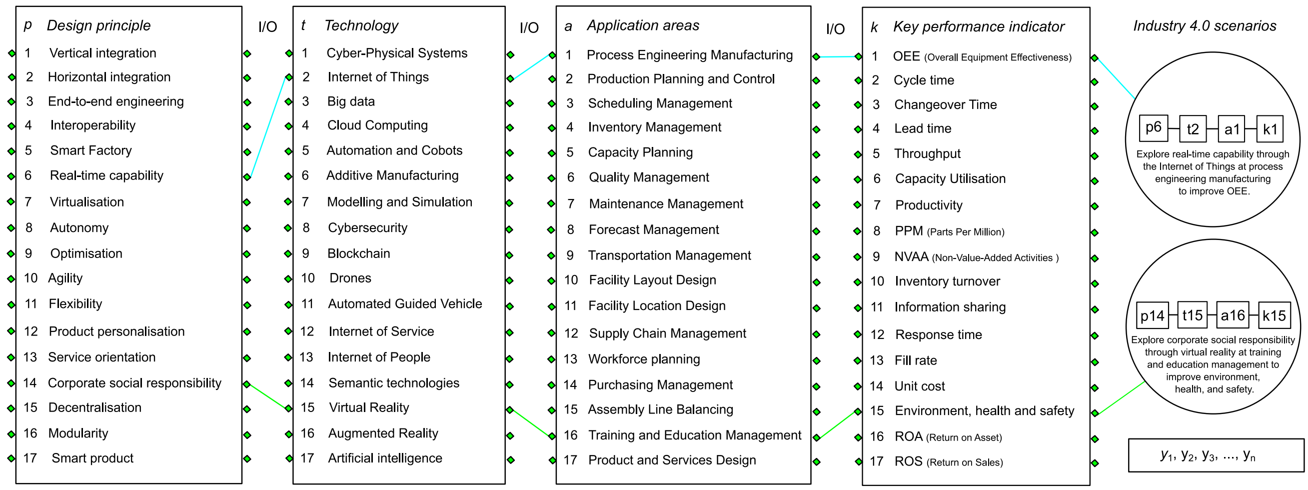


Figure 3: Industry 4.0 scenarios identification framework

Table 1
Main template

What?	How?	Where?	Why?
Explore <principle>	through <technology>	at <application area>	to improve <kpi>

translated from high to lower abstraction levels by following the RAMI4.0 [15, 74], which helps identify the most relevant industry standards to be combined with the respective front-end and back-end technologies for its implementation in a company.

In order to test the proposed framework, thirty-four I4.0 scenarios were generated, following a stratified sampling, covering all principles and technologies in Fig. 3. Then, they were verified related to empirical evidence available in the literature. To identify the real cases of I4.0 implementation, a literature review was conducted in electronic databases searching: Web of Science, Scopus, and Google Scholar from July 2020 to December 2021. Specifically, articles of which the title, abstract, or keyword include "Industry 4.0" or "Industrie 4.0" and "case stud*" or "use case*" or "show case*" or "application scenario*" and were published between 2011 and 2021 were searched. The article's reference list (backward snowball sampling) and citations to the article (forward snowball sampling) were then analysed to identify additional relevant references [75]. Only cases with company names were considered for verification and identification of complementary information (e.g. company size, location) in company websites or other publications related to the case. In total, 684 use-cases of I40 were identified, as summarised in Tab. 2. The list of I4.0 scenarios and use cases selected is available in Appendix A.

The generation of I4.0 scenarios linked to real I4.0 use cases for benchmarking is a practical approach that may help overcome manufacturing SMEs' scepticism, hesitancy, and lack of clarity about the benefits of adopting I4.0, as pointed out in [27] as well as implementation barriers to move towards I4.0, such as the lack of expertise and tools [9].

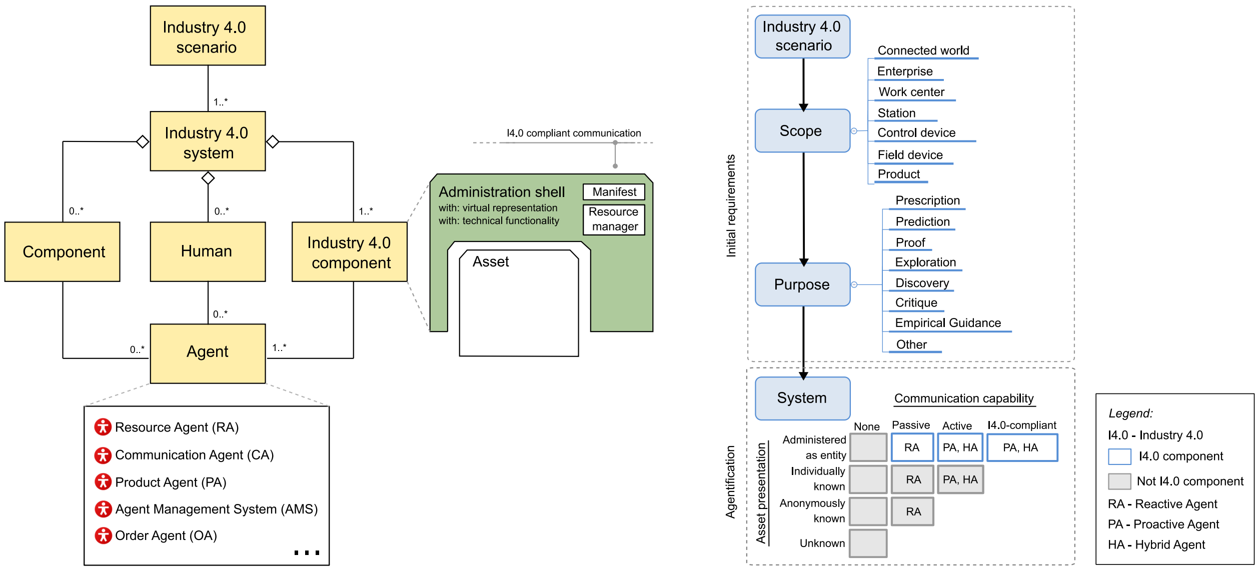
Table 2
Industry 4.0 use cases

Reference	Number of cases
RRI [76]	246
Plattform-I4.0 [77]	210
AIF [78]	175
Fettermann et al. [9]	38
Weking et al. [23]	32
Tao et al. [79]	8
CRIQ [80]	2
DHL [81]	1
Jensen et al. [82]	1
Vieira et al. [83]	1
Total	714
Total - Duplicates	684

4.2. A framework for analysing I4.0 scenarios

As illustrated in Fig. 4a, an I4.0 scenario, represents one or more I4.0 systems composed of I4.0 components, not I4.0 components, and people [15]. The term component refers to a physical or virtual asset that is something of value for an organisation (e.g. equipment, station, product, software, idea, service, document) and exerts a certain role in a certain system [41]. In the RAMI4.0, assets are mainly classified in terms of presentation (i.e. unknown, anonymously known, individually known, administered as entity) and communication capability (i.e. without, passive, active, I4.0-compliant) [41]. Based on this classification scheme, an I4.0 component, which characterises an asset, is either: (1) anonymously known with passive communication capabilities; (2) individually known with I4.0-compliant communication; or (3) administered as entity with I4.0-compliant communication, where entity refers to uniquely identifiable asset managed in the information world [41].

I4.0 components' properties include unambiguous identifiability, state in the lifetime (i.e. type, instance), I4-compliant communication capability via service-oriented



(a) Industry 4.0 scenarios modelling.

(b) Guidelines for defining the simulation problem domain

Figure 4: Industry 4.0 scenarios analysis framework. Adapted from [15].

architecture (SOA), virtual representation, technical functionality, nestability, and encapsulability [15]. Overall, I4.0-components are defined as "globally and uniquely identifiable participants capable of communication, and consist of the administration shell and the asset with a digital connection within an I4.0 system" [41, p. 24]. Essentially, the difference between a non I4.0 component from an I4.0 component is that the latter contains an administration shell, which records assets' lifecycle data and converts it into information, containing partial models from different domains [41].

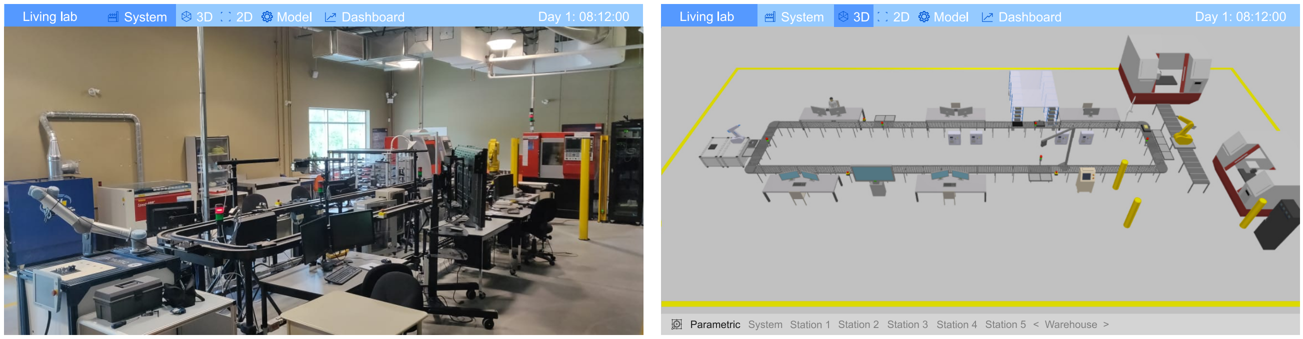
I4.0 systems can be analysed through RAMI4.0 architecture, as described in [84], that modelled an I4.0 demonstrator based on RAMI4.0. A similar approach to model I4.0 systems in mini-factories is proposed in [85]. I4.0 systems can also be analysed using agent technology since its properties (e.g. autonomy, reactivity, proactiveness, social ability, reconfigurability, modularity, learning capacity), matches I4.0 components and systems requirements [86, 87]. Taking this into consideration and in order to support the analysis of I4.0 scenarios through simulation modelling we propose some assumptions and general guidelines presented in Fig. 4bb, addressing part of the conceptual modelling phase, which is of fundamental importance for the development of simulation studies [88]. The main assumptions are as follows:

- There is an existing system non I4.0-compliant (base case scenario) for retrofitting based on the chosen I4.0 scenario (future state scenario);
- The chosen I4.0 scenario can be verified by domain experts involved in the simulation project;
- There is proper resources available to develop the simulation project and enough time for the model results to be useful considering the decision-making time window.

Following Fig. 4b the first guideline after defining an I4.0 scenario is to define its scope of application, i.e. the degree of granularity of the system for analysis based on the hierarchical levels of RAMI4.0 (i.e. product, field device, control device, station, work centres, enterprise, connected world), limiting system boundaries for modelling and analysis.

The second guideline is to specify the purpose or motivation for using simulation modelling relative to the I4.0 scenario since it influences simulation model design, i.e. conception, implementation, analysis. From [50] it can be classified into seven categories: (1) prediction — identify variables relationships and or making prognoses about future state; (2) proof — demonstrate that the modelled system can produce particular types of behaviours; (3) discovery — find emergent behaviours; (4) exploration — evaluate the conditions in which a certain behaviour is produced; (5) critique — evaluate pre-existing explanations for a particular phenomenon; (6) prescription — establish improved modes of operation; (7) empirical guidance — assist theories development. Other motivations for using simulation modelling in manufacturing includes system performance analysis, problem-solving, achieving common understanding or resolving dispute between stakeholders, identification of system design requirements, selling an idea, training and education [54, 58, 49, 16].

The third guideline is to identify the agents by distinguishing which assets composing the system to be modelled will be treated as I4.0 components and which will not, based on their presentation and communication capability, as represented in Fig. 4b, as well as their technical function, representation, and state in the lifetime (i.e. type, instance).



(a) Physical system (b) 3D model

Figure 5: Simulation model developed in AnyLogic software

It's worth mentioning that humans are also an asset in the model context, which complies with [63]. Moreover, It is important to highlight that "'what is modelled as an I4.0 component is a design decision" [84, p. 19], as well as the agents. Nevertheless, for simulation modelling purpose, this procedure gives a good indication of candidates for agentification, their behaviours (i.e. reactive, proactive, hybrid), as described by Wooldridge [89], and relationships, that are the main requirements to develop an agent-based model [54]. A detailed description of assets hierarchical arrangement, aggregation, and relationships are provided in [63] for reference. Another approach would be to adopt agent-based patterns and architecture for manufacturing, which enable the migration of legacy systems to I4.0 systems based on RAMI4.0, as proposed by Salazar et al. [87].

In addition, it is recommended to use the business process modelling and notation (BPMN) and/or unified modelling language (UML) as primary conceptual modelling tools, since both modelling standards are widely used in the context of I4.0 and simulation modelling [90, 91, 15, 49, 92, 93]. In particular, we consider BPMN for mapping business process flow, UML class diagram for agentification, UML sequence diagram to describe agents' interactions, and UML state diagrams to describe agents' behaviours. For reference, the use of UML formalism to represent asset administration shell is described in [93]. The use of BPMN and UML for simulation modelling is described in several studies, such as in [90], [91], [92] and [49].

5. Proofs-of-concept

5.1. Case of a living lab

The first proof-of-concept case was developed in a Canadian college centre for technology transfer (CCTT) with a focus on their living lab, where a testbed for I4.0 is being built to assist technological transfer to SMEs. An overview of the living lab's current physical infrastructure is shown in Fig. 5aa. It includes an automated storage and retrieval systems (AS/RS), a 90 degree closed-loop conveyor, a FANUC LR Mate 200iC robot arm, a CNC Lathe and CNC Milling machines from EMCO company, a 2D camera, and a UR5 collaborative robot (cobot) arranged in five stations to produce didactically prepared products.

The development of the case follows the general framework in Fig. 2. The first step was to assess the living lab's maturity level, also referred to as mini-factory. The CCTT has developed their own maturity model to assist SMEs. However, since the CCTT had not yet assessed the I4.0 maturity of its mini-factory and due to a non-disclosure agreement, we decided to adopt the self-assessment maturity model proposed by Lichtblau et al. [27] due to its practicality, focus on I4.0 technological dimensions, and available dataset of I4.0 readiness levels of German SMEs for comparison. Nevertheless, any other readiness/maturity assessment model could be used at this stage.

The I4.0 self-assessment was conducted with five project managers of the CCTT that have a comprehensive overview of the organisation's strategy. Based on the assessment results summarised in Fig. 6, the CCTT has an intermediate level of I4.0 readiness in the maturity dimensions strategy and organisations, smart factory, and smart operation, being classified as a learner; an outsider level in the dimensions smart products and data-driver services, classified as a newcomer; and an expert level in the dimension employee, classified as a leader. From the available assessment dataset in [27] of manufacturing SMEs with up to 99 employees, only 6.5% have reached level 2 in strategy and organisations; 10.1% reached level 2 in the smart factory; 36.1% reached level 2 in smart operations; 83.1% are level 0 in smart products; 92.3% are level 0 in data-driven service; lastly, only 4.1% have reached level 4 in employee maturity dimension. These results suggest that even in its current state, the mini-factory can help the manufacturing SMEs reach higher I4.0 maturity levels. However, much still needs to be done to promote I4.0.

After conducting the maturity assessment, we proceeded with a maturity gap analysis, as proposed in [32], considering a five-year period, where the following maturity items were prioritised for development: definition of indicators, equipment infrastructure, digital modelling, data collection, data usage, IT-systems, distributed control, and self-reacting processes. The next step would be to define the roadmap for the CCTT, following any available model in the literature,

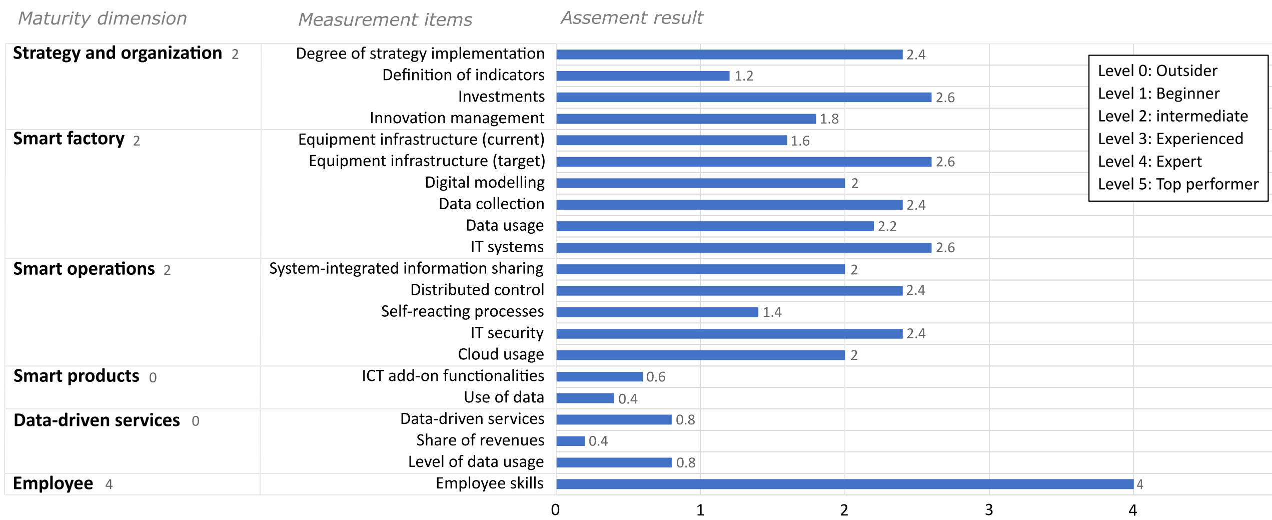


Figure 6: Industry 4.0 maturity assessment results

such as the one proposed in [33], introduced in Section 2.2. However, the CCTT has already defined a roadmap for their mini-factory for the next five years, mainly based on project grants. Nevertheless, they have defined a few concrete initiatives, having much space to incorporate new I4.0 projects. Therefore, the I4.0 scenarios identification framework in Fig. 3 was applied to refine their existing roadmap, where a total of twenty-five I4.0 scenarios were generated and one was selected based on the CCTT priorities for further analysis.

The I4.0 scenario identified through the framework in Fig. 3 selected for evaluation consists of exploring product personalisation and smart product through the Internet of Things at process engineering manufacturing to improve capacity utilisation. To give a better context, mass customisation (or product personalisation) is a manufacturing strategy that usually combines high production volumes with a high variety of products [94, 95]. The approach to the manufacture of customised products (i.e. process, policies, technologies) depends on the customisation configuration adopted, which can be identified and classified based on product modularity and the point of customer involvement for customisation in the production cycle, i.e. design, fabrication, assembly, or use [94]. In this sense, the mini-factory plans to adopt a cut-to-fit modularity approach based on parametric design, wherein customers can specify the dimensions and parameters changes to standard designs in the fabrication stage through a web application.

That being said, we proceeded with the application of the analysis framework in Fig. 4, limiting the scope of the I4.0 scenario selected for evaluation to the work centre that encompasses the five workstations. The main purposes chosen for the development of the simulation model were to define improved modes of operation (i.e. prescription); reach a common understanding between stakeholders; identify system design requirements; and education and training. The main assets composing the system to be modelled as I4.0 components are the order management system and smart

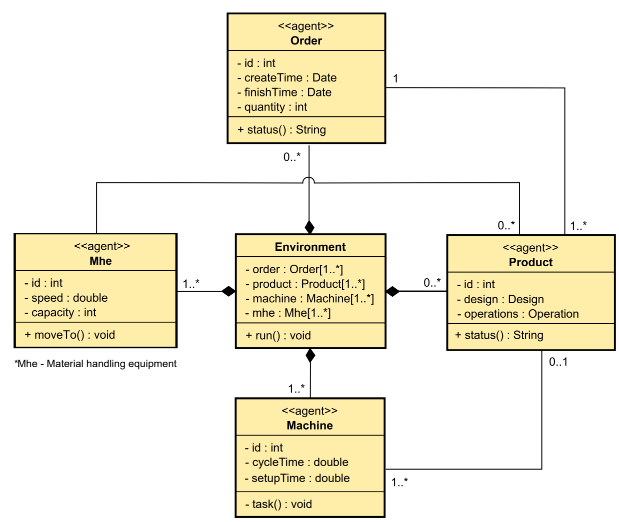


Figure 7: Simplified UML class diagram

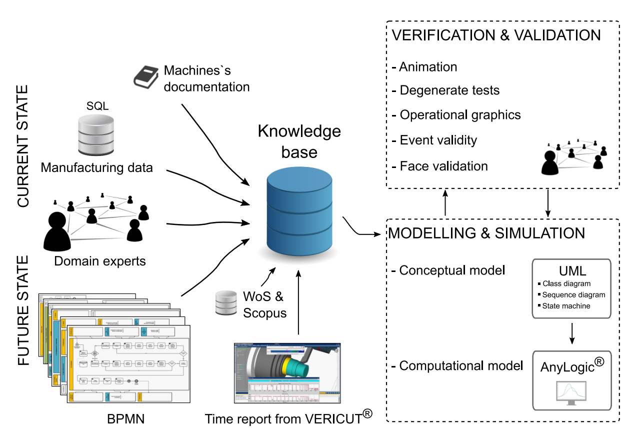
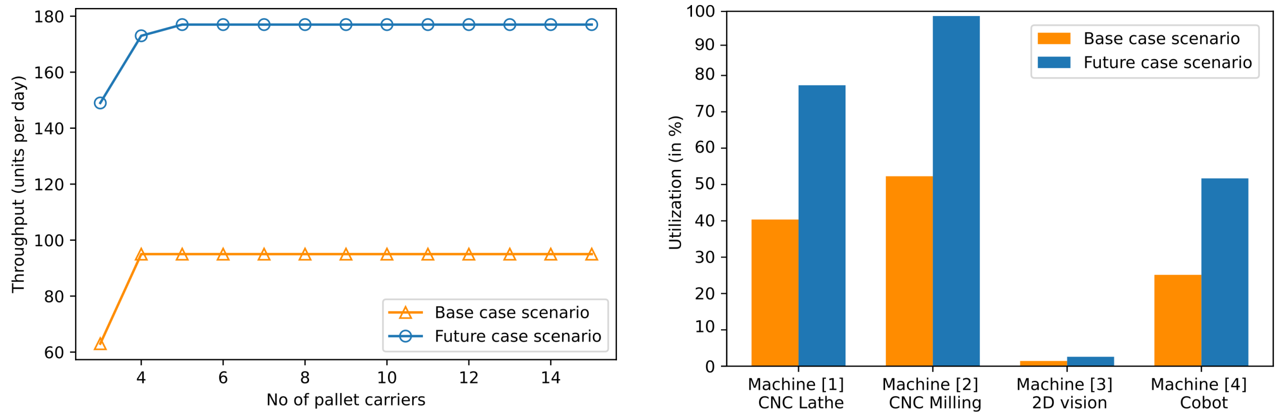


Figure 8: Modelling process



(a) Throughput rate

(b) Average machines utilisation

Figure 9: Simulation experiments result

products, managed as entities with active communication capabilities. Other important components are the processing machines and material handling equipment that are individually known components with active communication capabilities, therefore classified as non I4.0 components. Furthermore, based on Fig. 4b all these components can be modelled as hybrid agents.

The agentification is represented in Fig. 7 as a UML class diagram. The order agent (OA) manages the orders placed by customers via a cloud web application. The product agent (PA) represents a smart product, i.e. a pallet with a working piece at the warehouse equipped with an RFID tag that can communicate with other agents through RFID tag reading and writing. The PA records the order specification in its RFID tag and requests services (e.g. transportation, processing, inspection) to other agents until it reaches its final state and is delivered to the customer. The material handling equipment agent (Mhe) is responsible for carrying the smart product along the production line and or placing it in a buffer or working station for processing, such as the AS/RS, circular conveyor, and FANUC robot arm. The machine agent (MA) is responsible for machining, assembly, and inspection, such as the CNC Lathe, CNC Milling, Cobot, and 2D machine vision.

An overview of the modelling process for simulation adopted is shown in Fig. 8. First, the mini-factory current state was modelled and simulated to identify improvement opportunities and validation. The future state, which comprises the I4.0 components, was then modelled and simulated under different what-if scenarios to analyse system configurations, identify engineering requirements, and estimate operational performance gains. As indicated in Fig. 8, different data sources were used to develop the simulation model, including data collected in the living lab, i.e. manufacturing data, machines' documentation, layout, time report from VERICUT CNC simulation, process data, as well as consultation with domain experts and Web of Science (WoS) and Scopus databases.

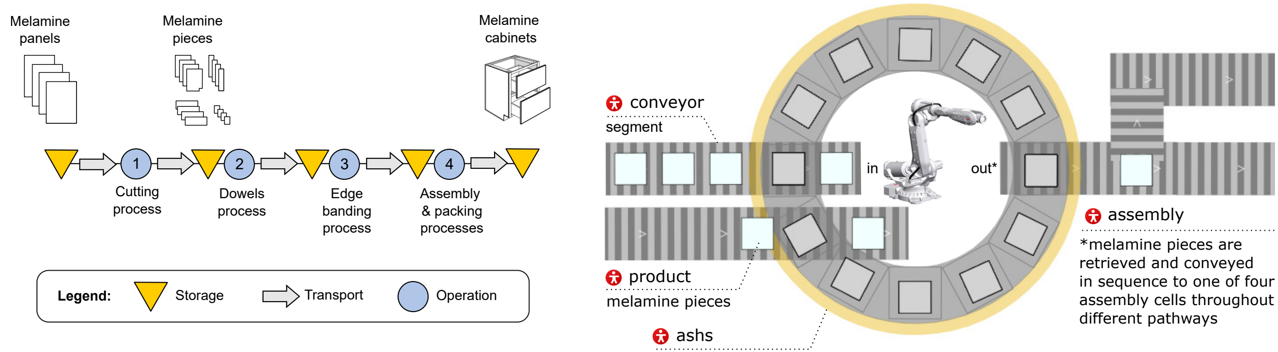
Table 3
Input data for the simulation experiment

Agent	Extends from	Station*	Processing time
AS/RS	Mhe Agent	1	32 s
CNC Lathe	Machine Agent	2	120 s
CNC Milling	Machine Agent	2	160 s
FANUC	Mhe Agent	2	30 s
2D Vision	Machine Agent	3	2 s
Worker	Operator	3	2 s
Conveyor	Mhe Agent	1 to 5	**

*Station where the machine is allocated. **Conveyor length = 18 metres, conveyor speed = 0.7642 ft/sec, number of pallet carriers available = 15. Note: 2 buffer positions at station 2 and 4 buffer positions at station 4 are available in the future state scenario.

The computational model was developed using the multi-paradigm simulation software AnyLogic® (version 8.7.2), following a hybrid simulation (HS) approach that combines DES with ABS to implement the model, where the DES model represents the process flow and ABS the hybrid agents. An overview of the simulation model is presented in Fig. 5b. Based on the classification framework for HS proposed in [52], the approach adopted in this study is an interaction type of hybridisation, where sub-models interact cyclically at runtime. The conceptual and computational model was verified by researchers and validated by six domain experts (e.g. project managers, technicians) working at the CCTT and participating in the project to transform the mini-factory towards I4.0. This approach is referred to in the literature as face validation, an important method for verifying and validating simulation models [96]. Moreover, we used the operational graphics approach to validate the computational model, which considers the dynamical behaviours of performance indicators visually, 2D and 3D animation and performed some degenerated tests, such as increasing the number of pallet carriers in the conveyor that are other forms of verification and validation [96].

Different simulation scenarios and experiments were developed, including stochastic data and other variables of interest, such as multiple product design. However, this



(a) Production process (b) Hybrid simulation model

Figure 10: Overview of the production process and simulation model of the storage system

study focusses on presenting the main simulation scenario and experiments used in decision-making since the purpose is to demonstrate the overall approach application. The main simulation experiment defined by subject matter experts for analysis compares the existing system configuration, i.e. a centralised production system in which the CNC machines work in series with a future state scenario in which the CNC machines can work in parallel to execute the tasks published by the smart products. The hypothesis is that smart products would enable using buffer positions at station 2, where the CNC machines are located, resulting in capacity utilisation, throughput, and flexibility increase. Tab. 3 summarises the data used to carry out this particular simulation experiment.

First, a sensitivity analysis was performed to identify the number of pallet carriers in the conveyor that maximises throughput. The results in Fig. 9aa indicate that the system should operate with at least 5 pallet carriers. Second, a simulation experiment to assess machines utilisation was conducted considering 5 pallet carriers and 8-hours run length terminating simulation. The results presented in Fig. 9bb supports the hypothesis that the new system configuration enables a significant increase in all machines' utilisation and throughput. No peak periods during the day were observed. Moreover, the new system configuration increases the flexibility of the system to deal with high product mix, preventing deadlock, considering that some products variants do not require service form all machines.

The simulation model contributed to raising fruitful discussions among CCTT members about system configuration, engineering requirements, the relationship between ongoing projects, and strategies for implementing I4.0 scenarios in the mini-factory. These discussions occurred mainly during data collection and meetings animated by the researchers to validate the model. Moreover, it helped CCTT members better understand their existing system and reach a consensus on future states, considering that the mini-factory does not operate continuously, making it difficult for them to observe certain behaviours. They also indicated an interest in adapting the model to analyse other I4.0 scenarios and experiments to generate data and develop a training and testing platform for artificial intelligence-related projects. Overall, they found the proposed approach very useful, suggesting that it can be applied to support manufacturing SMEs' transition towards I4.0, especially during I4.0 roadmap development and early stages of I4.0 projects implementation.

5.2. Case of a Manufacturing SME

This second proof-of-concept case was developed in a Canadian SME from the furniture and related product manufacturing sector, investing 3-5 million dollars to move towards I4.0 assisted by the CCTT, envisioning (in the medium to long term) an order-controlled production and adaptable factory [38]. The company produce cabinets for the residential, renovation, and commercial sectors. Fig. 10aa shows an overview of their current production process. First, the melamine panels (raw material) go to the cutting process, equipped with two CNC nesting tables and a cutting-stock-optimisation algorithm to minimise material waste. Next, the melamine pieces are manually identified and handled to subsequent processes (i.e. dowels and edge banding). Then, the melamine pieces are stored until all parts required to assemble a module are available to be manually batched and forwarded to one of four assembly cells. After that, the melamine cabinets are stored until they fulfil a contract and be shipped.

This proof-of-concept case focused on testing the framework for identifying and analysing I4.0 scenarios described in Section 4.1 and 4.2. Other elements (e.g. maturity assessment) were explored by the company with the help of the CCTT. The I4.0 scenario selected for analysis based on the framework in Fig. 3 consists of exploring real-time capability, decentralisation and flexibility through business and industrial automation at inventory management and production planning and control to improve Non-Value-Added Activities (NVAA) and fill rate, characterised in terms of flexible systems and machines. Continuing with the framework in Fig. 4, the scope of analysis was limited to a station. The main purposes chosen for developing the simulation model were to validate engineers' design choices and define improved modes of operation. The main I4.0 components in the system, managed as entities with active communication capabilities, are the conveyor, automated storage and retrieval system (AS/RS) with a robotic arm and the assembly cells, modelled as hybrid agents. Other important non I4.0 components are the products that are individually known components with passive communication capabilities.

Fig. 10b presents an overview of the hybrid simulation model, validated by a field expert (i.e. face validation) and by conducting sensitivity analysis, degenerated and extreme condition tests [96]. The 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 would follow a similar solution presented in [97]. Once the AS/RS Agent perceive the presence of a Product Agent (PA), i.e. melamine piece, it reads its information, checks if there is a storage space and executes the operation. Once the AS/RS receive a work order from an assembly cell, it checks the schedule and if all pieces to form a module is available to execute the work, placing the pieces at the conveyor in sequence to be transported to the assembly cell. Each melamine cabinet is composed of 9 melamine pieces, in average. The conveyor checks the target destination of the piece and proceeds with the transportation.

One of the main question the simulation model in Fig. 10b sought to answer is whether or not the circular AS/RS with a single robotic arm integrated with a conveying system would be capable of matching the demand, supplying parts to four assembly cells operating in parallel for different types of products with different cycle time. The simulation experiments result in Fig. 11, which compare the fill rate with different AS/HS average cycle times for unit load, suggest that the proposed system would only be able to match the demand of one assembly cell that produce standardised melamine modules. Overall, applying the proposed approach helped the company to identify I4.0 scenarios, test I4.0 systems design choices, define improved modes of operation and select I4.0 related projects for realisation, refining and detailing their I4.0 roadmap.

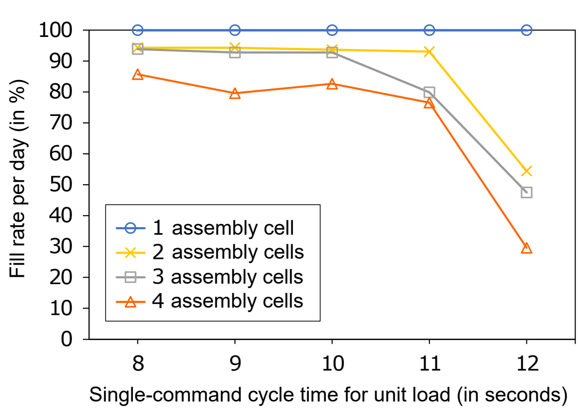


Figure 11: Fill rate analysis for the system with an AS/RS

6. Discussion

The study's results indicate three essential building blocks to support I4.0 realisation (i.e. maturity model, a roadmap, and a reference architecture), which combined may function as a holistic approach to address the development of I4.0 initiatives in SMEs. Furthermore, this study suggests modelling and simulation as a cost-effective approach to minimise risks during the development of I4.0 initiatives. It is especially useful for I4.0 scenarios that may require significant financial resources, changes in infrastructure, processes, operations, work organisation, or business models by allowing their analysis in a risk-free virtual environment to assist project conception, portfolio selection and planning during I4.0 roadmap development.

Even though the general framework presented in Section 4 seems intuitive, there is still a lack of shared understanding of I4.0, and it is not yet well-established in practice [13, 7]. Moreover, methods and tools to help companies move towards I4.0 are still scarce [9], especially for SMEs, where most "SME oriented tools, frameworks and models do not extend beyond giving a current I4.0 readiness state of an organisation" [13, p. 3]. Furthermore, the existing studies on I4.0 roadmap do not highlight the importance of other elements composing the framework, such as adopting a reference architecture and mechanisms to help identify, model, and simulate I4.0 scenarios. Therefore, it may provide companies with new insights into the steps and tools to facilitate their future adoption of I4.0 principles and technologies to improve their operational performance.

This study emphasises the importance of adopting a reference architecture for implementing I4.0 scenarios in a company while it increases its digital capabilities and I4.0 maturity levels. It can help fulfil the lack of norms and standards related to the implementation of I4.0 concepts pointed out by several SMEs [27] by abstracting and linking I4.0 architectural aspects to proven industry standards and providing recommendations of technologies and guidelines for modelling and implementing I4.0 systems [15, 40, 39].

In contrast to an I4.0 maturity model, which can easily be applied through an online self-assessment, developing an I4.0 roadmap may be challenging for SMEs due to a lack of expertise and scarcity of financial resources. To help address this issue, this study presents a more intuitive technology-based approach to identify I4.0 scenarios that can be implemented based on small-scale projects, which may help SMEs to identify particular areas of their business that could be positively impacted by I4.0 and overcome initial barriers in adopting I4.0, e.g. lack knowledge and technology awareness limitations [9, 17, 13].

The framework for identifying I4.0 scenarios presented in Section 4.1 gathers the main constructs of I4.0 (i.e. design principles, technologies), application areas and performance measures considered in industrial engineering and operations management (OM) fields to help manufacturing SMEs operationalise I4.0 concept into several I4.0 scenarios that can be roadmapped and implemented to improve their operational performance. This approach is supported by previous research, such as the one conducted by Fettermann et al. [9, p. 263], which suggest that "the identification of technologies associated with OM areas can help to understand how

Industry 4.0 can improve the performance of the operations in companies". The proposed framework extends previous research by incorporating and combining new constructs and technologies innovatively to put forward new ideas, connections, insights, and perspectives to facilitate the identification of I4.0 scenarios. Moreover, the I4.0 cases presented in Appendix A, considered to test the proposed framework, may help elucidate the fuzziness of understanding about the I4.0 through actual application examples.

In addition to that, the framework for analysing I4.0 scenarios presented in Section 4.2 provides guidelines for developing simulation models of numerous I4.0 scenarios based on a hybrid simulation approach that combines agent-based modelling and simulation with discrete-event simulation, which can be used to support I4.0 roadmap development and the realization of I4.0 initiatives. Alongside digital twin, hybrid simulation is featured as a leading simulation-based approach in the context of I4.0 [16]. Nevertheless, although modelling and simulation offer great potential to support I4.0, "particularly in SMEs, it is still not standard practice to use model-based simulations in order to configure and optimise manufacturing processes," which represent a significant challenge for I4.0 [1, p. 43] and may limit the application of part of the proposed framework.

7. Conclusion

This study addressed the lack of methods and tools to help companies transition towards Industry 4.0 (I4.0), especially for SMEs, by introducing a new framework to facilitate the identification and analysis of I4.0 scenarios for implementation, following a technology-based approach and focussing on small-scale projects to improve companies' operational performance as they increase their digital capabilities. It gathers the main I4.0 constructs and practices and considers modelling and simulation an effective approach to support project conception, portfolio selection and planning during I4.0 roadmap development and execution.

The proposed framework was tested through an I4.0 use-cases survey and two proof-of-concept cases. One case was developed at a Canadian college centre for technology transfer (CCTT) building an I4.0 testbed, and another one at a Canadian SME from the furniture and related product manufacturing sector transitioning towards I4.0.

In total, 684 cases of I4.0 implementation were identified in the use-case survey, and 34 scenarios of I4.0 were generated and verified according to empirical evidence in the literature. Moreover, 26 other I4.0 scenarios were generated and two were selected for analysis involving modeling and simulation in the proof-of-concept cases. The results suggest that the overall proposed approach is effective in helping manufacturing SMEs move towards I4.0. Nevertheless, most SMEs will require further technical assistance and accompaniment in their journey to I4.0, especially to acquire new technologies and comply with related industrial standards.

Limitations of this study include the fact that the overall framework's application may be subject to contextual factors (e.g. country, company size, sector). Further research in manufacturing SMEs is needed to fully explore the proposed framework's potential applications, considering other I4.0 scenarios with different principles, technologies, application areas, performance metrics, and simulation models with more complex behaviour. Future studies may also consider using modelling and simulation to assess the risks, costs, revenue potential, and implementation barriers to help companies' transformation to I4.0. Lastly, future research includes: developing an online platform to assist SMEs in implementing I4.0 technologies, considering that existing platforms are still very limited in scope; developing a software library to facilitate modeling and simulation of I4.0 scenarios; sophisticating the proposed framework by connecting I4.0 application examples and I4.0 application scenarios with I4.0 business models and by exploiting continuous technological advancements that enable intelligent, dynamic, and adaptive production and logistics systems; and investigating human aspects and human modeling in I4.0 systems.

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CRediT authorship contribution statement

William de Paula Ferreira: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. Fabiano Armellini: Methodology, Supervision, Validation, Funding acquisition, Writing - review & editing. Luis Antonio de Santa-Eulalia: Methodology, Supervision, Validation, Funding acquisition, Writing - review & editing. Vincent Thomasset-Laperrière: Resources, Supervision, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Industry 4.0 scenarios and cases

No	Scenario	Case Description	Company	Size	Location	Reference
1	Explore agility and corporate social responsibility through augmented reality at process engineering manufacturing and quality management to improve non-value-added activities, environment, health and safety.	Use of smart glasses instead of conventional scanner terminals during the picking process to increase efficiency by eliminating time-consuming errors and ergonomics by allowing employees have both hands free through a pick-by-vision solution based on AR.	Volkswagen	Large	Germany	[77]
2	Explore autonomy through automated guided vehicles at supply chain management to improve non-value-added activities, productivity, and inventory turnover.	Use of autonomous transport vehicles interlinked with each other and capable to interact with employees to increase productivity by reducing manual transport expenses and stock.	Bosch	Large	Germany	[77]
3	Explore interoperability, vertical and horizontal integration through semantic technologies at product and service design to improve information sharing.	Develop machines with flexible data exchange (e.g., manufacturer-independent, open data interfaces) based on OPC-UA technology that can be easily integrated vertically and horizontally into customer networks to increase data and information transparency as well as to create new business models (e.g., leasing of machines).	Mosca GmbH	Large	Germany	[77]
4	Explore real-time capability through the internet of things, big data and cloud computing at process engineering manufacturing to improve OEE and productivity.	Implementation of a real-time performance management system to increase transparency and improve operational performance (e.g., work productivity, OEE, value-added time).	Schneider Electric SE	Large	France	[98]
5	Embrace service orientation through the internet of services on transportation management to increase return on sales.	Embedded IoT sensors inside tires to offer new services and increase revenue by helping truck fleet drivers reduce fuel consumption and truck fleet managers to pay for tires based on kilometer-driven bases, moving from industrial to product-service company.	Michelin	Large	France	[99]
6	Explore flexibility and agility through big data, modelling and simulation at supply chain management to improve lead time and fill rate.	Combining big data and simulation modelling to analyse and minimize supply chain disruption risks.	Bosch Car Multimedia	Large	Portugal	[83]
7	Explore virtualization through modelling and simulation at maintenance management to improve information sharing and response time.	Using Digital Twin for planning, operations and maintenance of a power system to improve decision-making response time.	Siemens AG	Large	Finland	[79]
8	Explore real-time capabilities and virtualisation through modelling and simulation at production planning and control to improve information sharing, response time, and inventory turnover.	Use Digital Twin to provide a comprehensive real-time view of factory performance to identify improvement opportunities and enhance response time, on-time delivery, and material flow.	Baker Hughes	Large	USA	[100]
9	Exploring virtualisation through virtual reality at training and education management to improve environment, health and safety and compliance to regulations.	Development of a virtual reality based system for emergency response training in industrial sites to reduce environmental risks.	Buncefield	Large	UK	[101]
10	Exploring real-time capabilities through the internet of things, cloud computing and artificial intelligence at process engineering manufacturing and transportation management to improve OEE and unit cost.	Implementation of real-time monitoring of assets to improve OEE, reduce transformation costs and increase competitiveness.	Re Alloys steel	Large	Poland	[102]
11	Explore virtualisation through blockchain at supply chain management to improve information sharing and leadtime.	Development of a supply chain platform based on blockchain technology used by key players in the global container shipping industry to enable trusted exchange of information and information transparency (e.g., tracking shipping containers, documentation), which contribute to reducing lead time and transportation costs.	TradeLens (Maersk/IBM)	Large	Denmark	[82]
12	Explore service orientation through the internet of things at maintenance management to increase return on asset and return on sales.	Using IoT to incorporate new digital services into pre-digital products to increase revenue, monitoring aircraft parts, components and systems to offer aircraft engine preventive maintenance and intelligent aircraft fleet optimization services.	GE Taleris	Medium	USA	[99]
13	Explore real-time capability through IoT, big data, and artificial intelligence at maintenance management and quality management to improve response time.	Developed a system to collect over 2 billion data points daily in real-time from around five thousand equipment's using IoT and applied Artificial Intelligence (i.e., machine learning and deep learning) to analysing the collected big data to improve semiconductor manufacturing processes through inspection image analysis and product yield monitoring.	Toshiba	Large	Japan	[76]
14	Explore interoperability through semantic technologies at process engineering manufacturing and supply chain management to improve information sharing.	Ensure the interoperability of their different digital platforms and IT-systems such as manufacturing execution system (MES), warehouse management system (WMS), enterprise resource planning (ERP), marketing, and B2B online commerce to improve information transparency.	ADFAST	Medium	Canada	[80]
15	Explore real-time capability and virtualization through the internet of things at inventory management, workforce planning, and quality management to improve information sharing, response time, NVAA, capacity utilization, OEE, and throughput.	Using IoT technology to monitor production lines, inventory, and updates on quality in real-time to improve information transparency (i.e., visibility and traceability) to drive faster decision making, addressing bottlenecks in material flow, quality problems, and labor inefficiencies. A 24% increase in OEE, a 10% increase in labor utilization efficiency, a 16% decrease in defects per million opportunities, a 10% decrease in inventory holding cost, and a 10% increase in throughput are reported.	Stanley Black and Decker	Large	Mexico	[103], [9]

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Table 4 – *Continued from previous page*

No	Scenario	Case Description	Company	Size	Location	Reference
16	Explore optimization through artificial intelligence at forecast management to improve inventory turnover and order lead time.	Use artificial intelligence to optimize procurement quantity to increase cash flow by decreasing inventory rotation days while preventing material shortages, ensuring on-time procurement of materials to enable order lead time promise of a minimum of 4 business days. A 60% decrease in demand forecasting margin error and a 50% improvement in inventory are reported.	NEC	Medium	Japan	[76], [9]
17	Explore decentralization and agility through additive manufacturing at product and service design to improve lead time.	Provide 3D printing services based on crowdsourcing and micro-factories, combining open-innovation, rapid-prototyping, and small-batch manufacturing to reduce product and technology development lead time.	GE Fuse	Medium	USA	[23]
18	Explore decentralization and product personalization through additive manufacturing at product and services design to improve unit cost and order lead time.	Provide 3D printing services through a full-service platform where designers can upload their 3D design (e.g., geometry, material) and sell the product through an online shop. The products are built on-demand using local micro-factories and deliver it to final customers.	Shapeways	Medium	USA	[23]
19	Explore smart products and service orientation through the internet of service at maintenance management to improve return on sales.	The company sells industrial cranes with remote monitoring to offer predictive maintenance services for a monthly fee.	Konecranes	Large	Finland	[23]
20	Explore service orientation through cyber-physical systems (CPS) at purchase management and inventory management to improve inventory turnover.	The company provides CPS® KANBAN full-service based on Kanban systems and principles to help customers make their warehouse and production more effective and transparent by increasing traceability and automating the replenishment and procurement process.	Würth Industrie Service	Large	Germany	[23]
21	Explore optimization through the Internet of Things at process engineering manufacturing to improve return on asset, environment, health and safety.	The company provides intelligent IoT-based energy-efficiency solutions based on activity-based lighting to customised workplace, adapting the light to employee based on their location and activity being executed.	Zumtobel	Large	Austria	[23]
22	Explore flexibility, agility, and optimization through artificial intelligence at process engineering manufacturing, capacity planning, and workforce planning to improve cycle time, OEE, and capacity utilization.	Use smartwatches and artificial intelligence for smart value stream management, enabling calculating and adjusting capacity and cycle time dynamically to optimize material flow and worker efficiency.	Baxter	Large	Germany	[77]
23	Explore end-to-end engineering integration through cloud computing, additive manufacturing, and cybersecurity at product and service design to improve information sharing.	The company provides a full-service 3D printing cloud-based platform using robust data management and top-level encryption to keep users' data safe.	Kabuku Inc	Medium	Japan	[76]
24	Explore descentralization and autonomy through drones at transportation management to improve leadtime and response time.	The company provides parcel delivery services to remote and or hard-to-reach areas by air using autonomous drones (i.e., flying postman).	DHL	Large	Germany	[81]
25	Explore real-time capability, decentralization, flexibility, and agility through the internet of people at inventory and transportation management to improve information sharing, response time, resource utilization, environment, health, and safety.	The company provides a full-service platform and app for humanitarian logistics, supporting transport coordination of aid agencies for freight-pooling and information transparency in the logistics chain to make relief aids reach the people in need more effectively.	Katkin	Medium	UK	[77]
26	Explore modularity and product customization through automation and cobot at process engineering manufacturing to improve changeover time, productivity, and response time.	Use product modularity to reach a lot size of one, enabling end customers to customize design and order skis through an online platform (custom shop), which is then produced in a local highly automated factory and delivered directly to the customers.	Atomic	Large	Austria	[23]
27	Explore modularity through automation and cobot at process engineering manufacturing to improve changeover time, capacity utilization, and response time.	Employed a modular production line following the plug & produce concept where process modules can be exchanged to enable the production of small batch sizes (i.e., high produce variance) and to optimize setup time and resource utilization.	Phoenix contact	Large	Germany	[77]
28	Explore flexibility and agility through automation and cobot at process engineering manufacturing to improve changeover time.	Adoption of new technologies (i.e., programmable welding robot, software tools) to reduce programming time and make the production process more flexible, enabling the manufacturing of smaller lot sizes to respond to a high demand diversification degree.	Radiatole	Small	France	[78]
29	Explore vertical integration through automation and cobot at process engineering manufacturing and scheduling to improve changeover time and non-value-added activities.	Developed a consolidated line controller named integrated line network box (iLNB) to monitor and control machines to perform automatic changeover based on the host system's production schedule, increasing the assembly systems' flexibility to cope with high product mix. A 30% increase in productivity is reported.	Panasonic	Large	Japan	[76]

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Table 4 – *Continued from previous page*

No	Scenario	Case				
		Description	Company	Size	Location	Reference
30	Explore smart factory through cyber-physical systems, internet of things, automated guide vehicles, artificial intelligence, automation and cobots at process engineering manufacturing, forecast management, production planning and control, scheduling, capacity planning, assembly line balancing, maintenance management, and supply chain management to improve information sharing, capacity utilization, OEE, lead time, inventory turnover, and response time.	The company adopts crowd-sourcing manufacturing to share 4M (Man, Machine, Material, Method) resources between factories and several other advanced manufacturing technologies (e.g., cobot, IoT, AGV, AI) along with a high degree of industrial automation to optimize the production processes, presenting several cases of Industry 4.0 implementation.	Hitachi	Large	Japan	[76]
31	Explore smart factory and end-to-end engineering integration through cyber-physical systems, automation, and cobot, artificial intelligence at forecast management, process engineering manufacturing, quality management, maintenance management, product and service design to improve productivity, unit cost, and response time.	Developed a new connected smart factory facility that relies on vertical integration, autonomous machines, e-commerce integration, manufacturing collaboration, machine cloud, and several other advanced manufacturing technologies (e.g., cobot, AI) to improve productivity, operating costs, and return on sales. A reduction of order lead time from 21 days to 6 hours is reported.	Harley-Davidson	Large	USA	[104], [9]
32	Explore product personalization and smart product through the internet of things, cloud computing, modelling and simulation, automation and cobot at product and service design, production planning and control, and scheduling management to improve fill rate, productivity, response time, and customer complaints.	Adopt an automatic order processing (i.e., E-Shop) to produce customized punching tools, wherein customers can configure the tool and place the order, automatically generating the CAD files to be transformed in machine programs. Furthermore, the workpieces are uniquely identified, marked with a neutral DataMatrix Code (DMC), storing customer order data from SAP, and communicating with the machines to request services. A 71% reduction of customer complaints, a 240% increase in on-time delivery, a 71% increase in productivity, and a reduction of order lead time from 4 to 1 day are reported.	TRUMPF	Large	Germany	[77]
33	Explore service orientation through the internet of service and big data at product and service design to improve return on sales.	Use big data from customer information to improve vehicle fuel efficiency and enhance customer value, identifying critical factors in engines' development and production to improve fuel efficiency.	MAZDA	Large	Japan	[76]
34	Explore real-time capability through the internet of things at scheduling management to improve non-value-added activities and productivity	The company uses a production schedule system that sends individual work instructions to each worker equipped with a wearable smart device to reduce unnecessary movement.	JTEKT	Large	Japan	[76]

Legend: small enterprises - 1 to 99 employees; medium enterprises - 100 to 499 employees; large enterprises - 500 or more employees.