Computers in Industry 138 (2022) 103623

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

The architectural design and implementation of a digital platform for Industry 4.0 SME collaboration

Zixu Liu[a], Pedro Sampaio[a,*], Grigory Pishchulov[a,b], Nikolay Mehandjiev[a], Sonia Cisneros-Cabrera[a], Arnd Schirrmann[c], Filip Jiru[d], Nisrine Bnouhanna[e]

[a] *Alliance Manchester Business School, The University of Manchester, Manchester, UK*
[b] *St. Petersburg State University, 7/9 Universitetskaya nab., St. Petersburg 199034, Russia*
[c] *Airbus Group Innovations, Hamburg, Germany*
[d] *CertiCon a.s, Prague, Czech Republic*
[e] *fortiss - Research Institute of the Free State of Bavaria, Munich, Germany*

ARTICLE INFO

Article history:
Received 3 September 2021
Received in revised form 22 December 2021
Accepted 24 January 2022
Available online 12 February 2022

Keywords:
Digital platforms
Industry 4.0
Digitalization
Enterprise systems architecture
Ontologies
Application integration
SMEs

ABSTRACT

This paper presents the architectural design and implementation of DIGICOR — a collaborative Industry 4.0 (I4.0) platform aimed at enabling SMEs to dynamically form supply-chain collaborations so as to pool production capacities and capabilities and jointly address complex supply chain requests. The DIGICOR architecture builds on the event-driven service-oriented architecture (EDSOA) model to support the collaboration between SMEs, dynamic modelling of their systems and services, and their integration in the supply chains of large OEMs, enforcing digital platform governance rules for knowledge protection and security. In contrast to the extant platforms assessed through our systematic review, the proposed architecture supports the entire lifecycle of I4.0 collaborations, from creation of viable teams to deployment and operation. The architecture provides an open and extensible solution for (i) creating a marketplace for the collaboration partners, (ii) providing services for planning and controlling the collaborative production, logistics, and risk management, while supporting APIs for third parties to provide complementary services such as advanced analytics, simulation, and optimization; and (iii) seamless connectivity to automation solutions, smart objects and real-time data sources. We report on the design of the architecture and its innovative artefacts such as the component model description and the semantic model constructs created for meaningful event exchanges between architectural end-points. We also describe a running use case demonstrating implementation scenarios.

1. Introduction

Industry 4.0 (I4.0) created opportunities for companies to adopt new technologies to gain competitive advantage in domestic and global markets through digital transformation (Hofmann and Rüsch, 2017; Gilchrist and Gilchrist, 2016; Koch et al., 2014; Lennon Olsen and Tomlin, 2019; Koleva, 2018). The I4.0 paradigm involves organizing production processes by the principles of inter-operability between physical and cyber systems, decentralization, real-time data analytics, service orientation, and modularity. Therefore, successful implementation of I4.0 principles and practices facilitates enterprise systems integration and collaboration across the value chain, self-adaptation of production systems, and agile response to customer demand (Smit et al., 2016; Xu et al., 2018). I4.0 technologies and application models can thus lower collaboration barriers and increase the effectiveness of collaborations in manufacturing supply chains (Ghadge et al., 2020; Dalenogare et al., 2018; Chiarello et al., 2018).

Rapidly adaptable supply networks and highly-connected organizations across the supply chain are seen as key enablers of I4.0 (Lasi et al., 2014; Obitko and Jirkovský, 2015; Camarinha-Matos et al., 2017), however, large original equipment manufacturers (OEMs), such as Airbus, often prefer to streamline their supply chains and reduce the number of Tier-1 suppliers to a small cohort of preferred

---

* Corresponding author.
E-mail addresses: zixuxilan@gmail.com (Z. Liu), P.Sampaio@manchester.ac.uk (P. Sampaio), grigory.pishchulov@manchester.ac.uk (G. Pishchulov), n.mehandjiev@manchester.ac.uk (N. Mehandjiev), sonia.cisneroscabrera@manchester.ac.uk (S. Cisneros-Cabrera), arnd.schirrmann@airbus.com (A. Schirrmann), filip.jiru@certicon.cz (F. Jiru), bnouhanna@fortiss.org (N. Bnouhanna).

https://doi.org/10.1016/j.compind.2022.103623
0166-3615/

suppliers (typically large companies such as Thales and Honeywell). In order to participate in supply networks of large OEMs, small and medium-sized enterprises (SMEs) need to develop collaborations with other organizations across the supply chain tiers in the form of clusters or virtual enterprises, which often demands integration of enterprise business processes and systems (Ferreira et al., 2016; Camarinha-Matos and Afsarmanesh, 1999; Gunasekaran et al., 2008; Trappey and Hsiao, 2008). Additional barriers for SMEs to join OEMs supply networks arise from risk sharing requirements when forming partnerships, complex procurement and collaboration procedures, contract formulation rules, and legacy IT systems (Schadel et al., 2016).

Furthermore, customer demands often involve novel features and short delivery schedules. These can only be managed through close collaborations between companies along the supply chain, operating as ad-hoc production networks. These networks often include innovative SMEs, and these need supportive information and communications technology infrastructure such as technical platforms, novel governance approaches, intellectual property protection mechanisms, and coordination tools to simplify the setup and management of ad-hoc production networks. Yet current state-of-the-art enterprise systems (Romero and Vernadat, 2016) including supply chain management (SCM) modules deployed at OEMs are mainly affordable to large Tier-1 suppliers and it is often too onerous for SMEs to integrate their operational processes and systems to enterprise SCM systems due to complexity and associated costs (Kazantsev et al., 2018).

Collaborative platforms with low barriers to integration and real-time data exchange capabilities are often seen as the way forward (Cisneros-Cabrera et al., 2017; Helo and Szekely, 2005; Ramzan et al., 2017). Digital platforms supporting dynamic formation and operation of supply chain collaborations can help overcome the challenges and barriers outlined above by offering tools and services accessible to companies of any size and scope. Joining such platforms would broaden supply alternatives for OEMs as well as new markets for SME suppliers, capturing the value creation opportunities associated with I4.0. Such platforms would also allow their members to form supply networks faster, scale and adapt to highly dynamic production requirements, and increase trust between partners through adoption and enforcement of platform-wide governance mechanisms (Camarinha-Matos et al., 2009; Mesquita et al., 2017).

Indeed, in many industries such as automotive and aerospace, product development involves collaborations between companies of all sizes operating across the globe. OEMs drive the development of new products engineered across several locations with partners collaborating via a supply network. Most relationships in this supply network are temporary, and today's project partner can potentially become tomorrow's competitor (Liese et al., 2013). In this context, companies may be unwilling to share business-critical information due to the perception that other parties can unfairly exploit the information for their own competitive advantage. Lack of trust among trading partners is associated with information sharing challenges in SCM (Ahluwalia et al., 2007). Lack of information sharing has been identified as a major reason for inefficiencies in SCM (Wang et al., 2005). Digital platforms can play a vital role in addressing these challenges by governing information flows across the supply chain and ensuring that intellectual property is protected and knowledge sharing happens without disclosing sensitive data.

Existing research on collaborative platforms in the context of I4.0 also identifies the need for an efficient communication medium to share complex information to support collaborations between companies (Koleva, 2018; Ferreira et al., 2016; Dallasega et al., 2018; Pulparambil et al., 2021). Collaborations created via the platform may terminate after a certain time, and the platform should be capable of managing all stages of the collaboration lifecycle, including formation, operation and dissolution. I4.0 platforms should also scale up to serving thousands of collaborations involving several thousands of companies (Camarinha-Matos et al., 2009). They also need to cater for a broad range of requirements and technical capabilities of the OEMs and SMEs collaborating on the platform. For example, in the context of our work, partners with extensive IT capabilities were receptive to the notion of pre-defined domain ontologies for information exchange and services interoperability using semantic notations such as OWL, while others preferred basic data format and exchange standards for systems integration. Platform architectures ideally should support architectural styles and patterns that promote flexibility and reduce collaboration barriers.

Our study aims at facilitating SME collaborations by addressing the barriers and challenges articulated above. Our main objective was to design and implement an I4.0 platform following a flexible and open architectural approach that supports setup and management of dynamic production networks and enables SMEs to embark on digitalized collaborations within the I4.0 context. The work discussed in this paper was conducted as part of the DIGICOR project[1] — a research and development initiative funded by the European Union and having the DIGICOR platform as its principal outcome. The architectural artefacts were derived following a systematic research method — the Design Science Research (Hevner and Chatterjee, 2010), departing from real-world requirements gathered from project stakeholders and producing an extensible architectural artefact that provides a basis for further technical developments in the area of I4.0 collaborations. The key contributions reported in this paper are:

1) The architecture design and its instantiation as a platform supporting dynamic modelling of systems and services provided by SMEs and integrating them into OEMs' supply chains. The proposed architecture enables SCM integration by specializing the event-driven service-oriented architecture (EDSOA) and middleware for interoperability and communication. Compared with other types of architecture such as service-oriented architecture (SOA) (Linthicum, 2016), services in EDSOA publish events, and other services that listen to these events update their data after consuming an event, which promotes flexibility and loose coupling between services (Zhang et al., 2014; Laliwala and Chaudhary, 2008).
2) The proposed architecture adds to EDSOA mechanisms for modular and efficient communication through semantically defined messages. This allows entities in the platform to (i) easily share complex information about capabilities, products, services, and the current state of collaborations; (ii) formulate new vocabularies needed to capture new business opportunities and models of collaboration, including shared understanding of collaborative processes. In addition to semantic-driven interoperability, the architecture also supports basic data formats and exchange standards, reducing the technical barriers to SME systems integration.
3) The proposed architecture also ensures compliance with case-specific governance rules, procedures for knowledge protection, and security (Zhou et al., 2015).

The remainder of the paper is structured as follows. Section 2 includes a literature review and a survey providing a comparative analysis of I4.0 platforms. The research methodology is described in Section 3. Section 4 outlines requirements and provides an overview of the architectural design based on requirements elicited from SMEs and OEMs operating in the automotive and aerospace industries. Section 5 presents key components of the platform

---

[1] Decentralised Agile Coordination Across Supply Chains (DIGICOR), www.digicor-project.eu

architecture. The platform implementation is described in Section 6. Section 7 concludes the paper, outlines managerial implications, limitations and future work.

2. Literature review and gap analysis of Industry 4.0 platforms

The development of digital technologies brings opportunities for organizations to create digital collaboration platforms for I4.0 use cases. Bitkom, VDMA, and ZVEI (Bitkom, 2015) report that I4.0 relies on securing communication and cooperation of all participants in real-time over the entire product lifecycle. This can be facilitated by digital platforms (Bitkom, 2015). Kagermann (Kagermann, 2015) analyzes the impact, challenges and opportunities of digitization and concludes that platform-based business models provide the foundations to underpin enhanced value creation in the age of I4.0. These papers support the claim that effective systems and platforms aligned with the current I4.0 trends are needed in the manufacturing industry and its supply chains (Longo et al., 2019; Büyüközkan and Göçer, 2018; Russo et al., 2018; Zo et al., 2019). We divide the literature on digital platforms and I4.0 into two streams.

The significance of the digital platforms is the focus of the first stream. Nowadays, large organizations run and maintain hundreds of independently evolving software systems. To adapt to I4.0 trends, SMEs face challenges to integrate their systems with industry partners due to the level of complexity and agility of information exchange needed to support industrial processes (Mukherjee et al., 2017; Sun et al., 2017). Purao et al. (2018) focus on performing systems integration using a proposed System Integration Requirements Engineering Modelling Language (SIRE-ML). Integration models built with SIRE-ML have the benefit of ensuring coverage and minimizing ambiguity and can be used to build digital platforms, middleware, services, and distributed objects. Reliable and timely data transactions and real-time communication are key aspects for achieving agile manufacturing goals. Zeng et al. (2019) propose a method to handle the data delay variance in networks for real-time Quality of Service in I4.0. A system architecture for time slot-based and Internet of Things (IoT)-based industrial switches is also proposed.

Systems architecture is one of the most important considerations in the design stage of digital platforms, and indeed several papers describe their architecture in detail. HewaNadungodage et al. (2019) introduce a Digital Environment to Enable Data-driven Science (DEEDS) which is a cross-domain, self-serve platform for data and computing that supports the entire end-to-end research investigation process. Wang et al. (2019) propose an integrated geographic information system platform architecture for processing and analyzing spatiotemporal big data. Kratzwald and Feuerriegel (2019) analyze different architectures used in question-and-answering (Q&A) systems, such as ontology-based and content-based Q&A systems. Table 1 provides details about the foundational technologies of the digital platforms reviewed in this paper. As the table reveals, EDSOA is not commonly used by extant platforms despite its advantages in flexible reacting approaches to events and promoting loose coupling between services. Due to these benefits, EDSOA was chosen as a basis for our system architecture and hence as the foundation for DIGICOR, thus enabling flexibility and simple integration of companies.

The second stream comprises papers describing *digital platforms based on I4.0 requirements.* Key requirement of digital platforms is the need to support the service ecosystems arising from the multitude of market players and service applications, and this can be done through implementing efficient digital marketplace mechanisms. A substantial review (Cisneros-Cabrera et al., 2017) of a representative set of marketplace platforms, such as the UK Government Digital Marketplace (Digital Marketplace, 2019), Alibaba (Alibaba.com, 2019), CloudBuy (cloudBuy, 2019), Amazon Business (Amazon Business, 2019), and Thomas net (ThomasNet®, 2019), provided a gap

Table 1
Survey and comparative analysis of Industry 4.0 platforms.

Platform name	Industry sectors supported	Architecture style/type	Communication	Knowledge protection and sharing mechanisms	Platform service extensibility approach	Implementation technologies
NIMBLE (Innerbichler et al., 2017)	Yes	Microservice infrastructure	Service-oriented	Data sharing service and product ontology	Hardcoded	Web interface, cloud-based microservice
IDARTS (Peres et al., 2018)	Yes	General layered architecture		Knowledge Management Component; data workflow	N/A	Java Agent DEvelopment framework (JADE)
IoT energy platform (Terroso-Saenz et al., 2019)	No	General layered architecture		UML class-based information model; data workflow	Hardcoded	Nimbits
RTMIIS (Zhang et al., 2015)	Yes	SOA	Service-oriented	N/A	Hardcoded	Cloud-based micro-service
Government affairs service platform (Lv et al., 2018)	No	SOA	Service-oriented	User service	Hardcoded	Web VRGIS engine, cloud-based microservice
A collaborative knowledge transfer platform (Cotrino et al., 2021)	No	General layered architecture	RESTful API	Database	Hardcoded	PHP, JavaScript, MySQL
Middleware for Intelligent Automation Platform (Coito et al., 2020)	Yes	Specialized middleware in general layered architecture	OPC UA Standard over Time Sensitive Networks	Cloud service and database warehousing	Hardcoded	Cloud-based microservice
Fog-of-Things platform (Verba et al., 2019)	No	Platform-as-a-Service	Message routing	Cloud service	Hardcoded	Cloud-based microservice
Automated flow-shop manufacturing system (Liu et al., 2019)	Yes	General layered architecture	OPC UA with database	Multi-view synchronization	Hardcoded	J2EE and Unity3D
SCM system with a blockchain-enabled architecture (Wang et al., 2020)	Yes	General layered architecture	Peer-to-peer blockchain network	Blockchain database; Traceability and visibility service	N/A	Validated by experts in SCM
Simulation Platform for Virtual Manufacturing Systems (Dobrescu et al., 2019)	Yes	SOA	Service-oriented	Cloud service and data store model	Service-oriented integration	Cloud-based microservice
DIGICOR (this paper)	Yes	Specialized EDSOA	Event-based	Authentication service and ontology layered architecture	App-store based	Angular 4 front-end, cloud-based back-end, Kubernetes

analysis to assess their support for I4.0 requirements. At the level of architecture, Li et al. (2018) analyzed and compared different smart manufacturing architectures such as the Smart Manufacturing ecosystem, Reference Architecture Model I4.0, Intelligent Manufacturing System Architecture, and the Industrial Internet Reference Architecture. The results show that the smart manufacturing architectures need to support rapid reactions to market changes. This requirement is consistent with the use of EDSOA in the design of the DIGICOR architecture.

Regarding individual platform proposals, Innerbichler et al. (2017) propose a collaborative I4.0 platform following a microservice-based architectural style. The platform enables IoT-based real-time monitoring, optimization and automated negotiations in manufacturing supply chains. Peres et al. (2018) propose a generic framework for data analysis and real-time supervision for predictive manufacturing systems in I4.0. Keshavarzian et al. (2019) propose a new architecture for an IoT platform in a function-as-a-service (FaaS) cloud model that solves scalability issues by running each function in a separate container. Further work proposes platforms based on generic layered architectures (Terroso-Saenz et al., 2019; Zheng et al., 2018; Liu and Jiang, 2016) and SOA (Zhang et al., 2015; Lv et al., 2018), however EDSOA was not used, despite its advantages. Verba et al. (2019) propose a Fog-of-Things platform and approach to measuring and estimating the runtime parameters and migration benefits of applications deployed in edge devices that carry out computations. Coito et al. (2020) focus on the development of standardized system architectures for Industry 4.0, proposing a middleware for intelligent automation, interoperability, determinism, and data structuring techniques to be layered over an industrial communication infrastructure such as the OPC UA standard over time sensitive networks. Wang et al. (2019) propose a blockchain-enabled architecture for supporting circular economy features and improving recycling in fashion industry supply chains. Blockchain technologies are used to allow handling of data privacy and security issues, and support provenance tracking.

Table 1 presents a survey and comparative analysis of a select set of I4.0 platforms assessing support for collaborative process requirements, identifying gaps, and contrasting with our work. Table 2 depicts architectural designs. Our analysis of collaborative process requirements coverage supported by I4.0 platforms reveals that most platforms have been confined to supporting simple collaboration approaches, where, for example, business-to-business (B2B) collaborations are formed by 1-to-1 matchings of two individual companies. Support for many-to-many collaboration design between companies (as in DIGICOR) is a major gap identified in extant platforms. These limitations arise primarily due to the slow adoption of collaborative networks research results into industry practice. Other gaps identified include the platform's functionality for connecting to external physical devices, third-party platforms, and the IoT vital to supporting SCM processes (Cisneros-Cabrera et al., 2017).

Support for semantic technologies (e.g., domain ontologies) underpinning platform interoperability and exchange of machine-readable information is also limited in industrial platforms. Semantic technologies can also lower barriers to forming SME clusters by providing meaning to machine-to-machine communications (Cisneros-Cabrera et al., 2021), by controlling or monitoring computer-based or machine-readable rules and procedures supporting digital governance of the entire platform ecosystem. Based on our comparative analysis of I4.0 platforms architectures, the following architectural issues were also identified:

The layered architecture style limits flexibility when designing large-scale open distributed systems. Minor changes in cross-cutting and connected layered components can trigger redeployment of the entire application. Scalability is another issue associated with layered architectures. The maintenance costs of a system of tightly

Table 2
Architectures used in the reviewed work.

Architecture type	SOA	Microservice infrastructure	Generic layered architecture	FaaS or IaaS (Infrastructure as a Service)	Specialized EDSOA
Platform source	(HewaNadungodage et al., 2019; Kochovski et al., 2019; Lv et al., 2018; Zhang et al., 2015; Dobrescu et al., 2019)	(Innerbichler et al., 2017; Liu et al., 2021; Wang et al., 2019)	(Kratzwald and Feuerriegel, 2019; Soille et al., 2018; Vaisband and Friedman, 2018; Peres et al., 2018; Terroso-Saenz et al., 2019; Liu and Jiang, 2016; Zheng et al., 2018; Coito et al., 2020; Liu et al., 2019; Wang et al., 2020)	(Alic et al., 2019; Keshavarzian et al., 2019; Verba et al., 2019)	DIGICOR (this paper) (Schipor et al., 2019; Almeida et al., 2019)

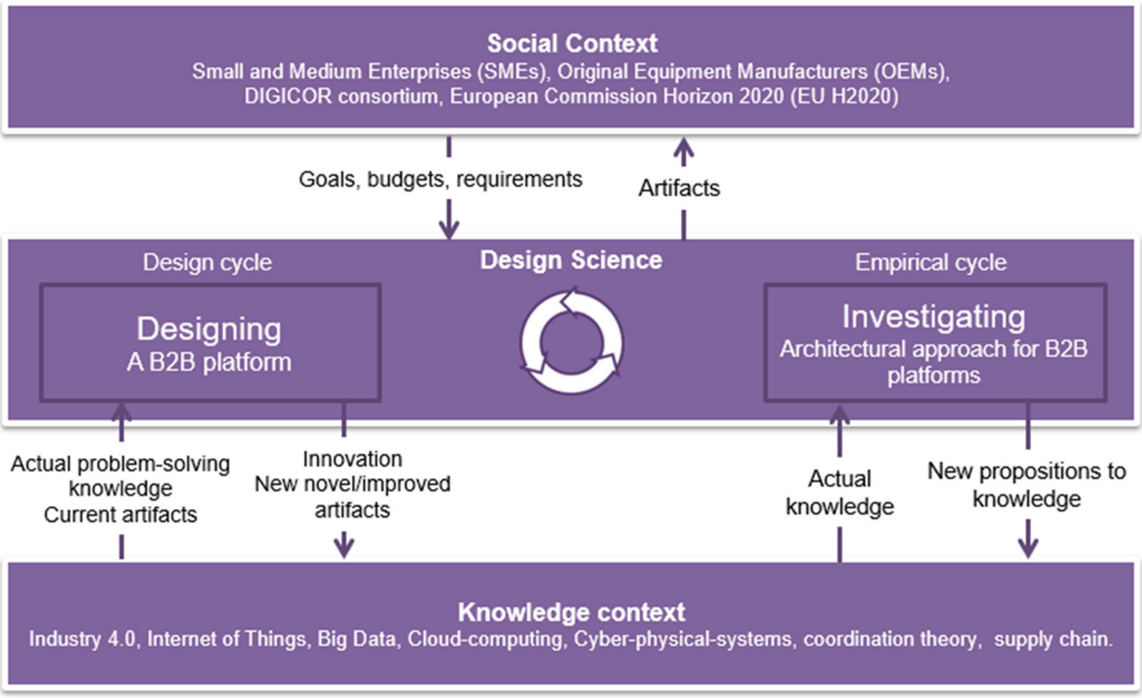


Fig. 1. Design Science Method applied in the development of DIGICOR.
Adapted from (Wieringa, 2014).

coupled layered components also grows exponentially with the increasing number of components.

The microservices architecture style due to its agility properties is widely adopted in the design of IoT platforms (Li et al., 2018; Vresk and Čavrak, 2016). However, this architecture style does not naturally lend itself to support high-performance data-intensive applications due to the distributed nature of microservices architecture and the potential need to replicate databases across services.

The event-driven architecture style has challenges associated with testability. Despite the ability to test each component individually, it is difficult to test the entire system behavior due to the large number of possible interactions. Another issue with this style is the high complexity of the development (Zhang et al., 2014).

As discussed in the Introduction, establishing efficient, effective, and trustworthy collaboration while protecting intellectual property is vital to maintain organizational competence in today's global business environment. Trust, confidentiality, and integrity issues involved in sharing data are immense. Platforms with simple collaboration approaches cannot fulfil such requirements. The gap analysis also identified that currently there is no architecture embracing all assessed capabilities. Notwithstanding, the literature review and gap analysis provided a body of knowledge on technical architectural designs and styles that influenced our architecture which was developed based on a specialization of EDSOA and intends to close the gaps identified above, by enriching EDSOA communication with semantically defined messages, implementing many-to-many collaboration design, and supporting digital governance.

3. Research methodology

The development of the architecture and the DIGICOR platform followed the Design Science Research (DSR) method (Wieringa, 2014), see Fig. 1. According to (Vom Brocke et al., 2020) page v, "the goal of DSR is to generate knowledge on how to build innovative solutions to important problems in the form of models, methods, constructs, and instantiations". The *research problem/question* of understanding collaboration barriers and challenges faced by SMEs in the context of I4.0 and proposing novel information systems artifacts (i.e., digital platform implementing new collaboration processes underpinned by an open and flexible IT architecture) to mitigate the barriers and address the challenges called for a constructive research paradigm such as DSR in contrast to quantitative or qualitative research methods as outlined in (Creswell and Creswell, 2017). The choice of the particular DSR method used in our research (Wieringa, 2014) was motivated by its extensive treaty on DSR, its coverage of the six core dimensions of a DSR project: 1. Problem description; 2. Input knowledge; 3. Research process; 4. Key concepts; 5. Solution description; and 6. Output knowledge (vom Brocke and Maedche, 2019), the availability of detailed guidance on the DSR process, and also our previous research experience with the use of the method in the development of research artefacts.

For the work reported in this paper, our core artifacts are the architecture and the platform, and their development within two contexts categorized as the social and the knowledge context. Firstly, the social context for our research comprises the manufacturing domain, particularly SMEs, OEMs and the requirements set by the DIGICOR consortium, involving stakeholders from the aerospace and automotive domains, as well as the specifications set in the European Commission's funding call (European Commission, 2015). Secondly, the knowledge context comprises the state-of-the-art developments of the literature on I4.0, IoT, big data, cloud-computing, cyber-physical systems, coordination theory, and supply chains.

DSR guidelines (Hevner et al., 2004; Hevner and Chatterjee, 2010; Wieringa, 2014) were also applied in the activities of the DIGICOR project including requirements elicitation, iteration with end users,

Table 3
Activities included in the development of the architecture and the platform.

Description	Objective	Method	DSR applied	Outcome
Requirements elicitation	Collect initial requirements from experts in the automotive, robotics and aerospace industries	Workshop	Guideline 1: Design as an artifact,Guideline 2: Problem relevance	Initial set of requirements and the problem scope as observed by the experts and stakeholders.
Demonstrations from early mockups to the final release version	Validate the utility, quality and efficacy of the platform	Survey and demo showcase	Guideline 3: Design evaluation,Guideline 6: Design as a search process	Implementations were updated following experts' opinion and validations.
Publication of research outputs from the work carried out to develop the platform	Contribute to knowledge in the information systems, data management, and SCM areas	Different methods applied in research publications	Guideline 4: Research contributions,Guideline 5: Research rigor	20 research outputs (https://www.digicor-project.eu/publications).
Presentation of DIGICOR at several venues	Inform the audience about DIGICOR and its outcomes	Showcase, focus groups, demonstrations	Guideline 7: Communication of research	DIGICOR is known to a wider audience. Details: https://www.digicor-project.eu/blog-1
Validation of the architecture	Please refer to Table A1 (in Appendix) for details.			

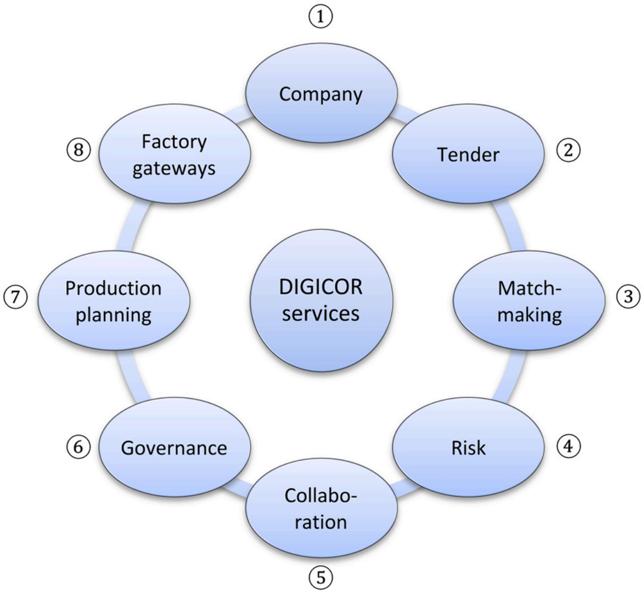


Fig. 2. Vision shaping the DIGICOR platform.

intermediate releases, validation and final release. Table 3 lists the activities that were carried out in the development of the proposed architecture and the platform, and the DSR guidelines applied on each activity. Table A1 in the Appendix includes the anonymized details of the participants of the activities listed in Table 3. All participants were stakeholders from the manufacturing sector associated with the aerospace, automation/robotics industry, and/or automotive industries, with experience and knowledge of SME collaborations.

4. Architecture overview

4.1. Requirements

This section presents the requirements associated with collaborative platforms in the context of I4.0. These requirements motivate the proposed DIGICOR architecture and platform. Fig. 2 schematically presents the vision shaping the DIGICOR platform. It has been conceived as a federation of services that would support the full cycle of activities needed for initiating and operating supply-chain collaborations, by letting companies to (1) register on the platform, describe their capabilities, and (2) post requirements for certain products and services. Based on this, the platform shall be able to (3) determine potential collaborations between member companies by matching their capabilities to requirements, and gauge the collaboration fit alongside (4) the risks involved. When a collaboration becomes formed (5), the platform shall support its operation throughout the collaboration lifecycle, while (6) enforcing governance rules. Further, it shall offer (7) production planning facilities to the collaboration partners, and (8) gateways to factory systems for accessing shop-floor data to warrant real-time visibility into the collaboration progress (Pishchulov et al., 2022).

Fig. 3 further presents the industrial context shaping the DIGICOR platform, which involves two SME clusters — automotive and aerospace, located in Germany and Wales. SME clusters have played a key role in elicitation of requirements for the platform, which we present below in greater detail. As shown in Fig. 3, platform services are organized into basic and tool-store services, the latter including any third-party services (see below). Encircled numbers in the figure are mapping its elements to the functionalities in Fig. 2. Requirements elicitation and development of the platform have spanned a period

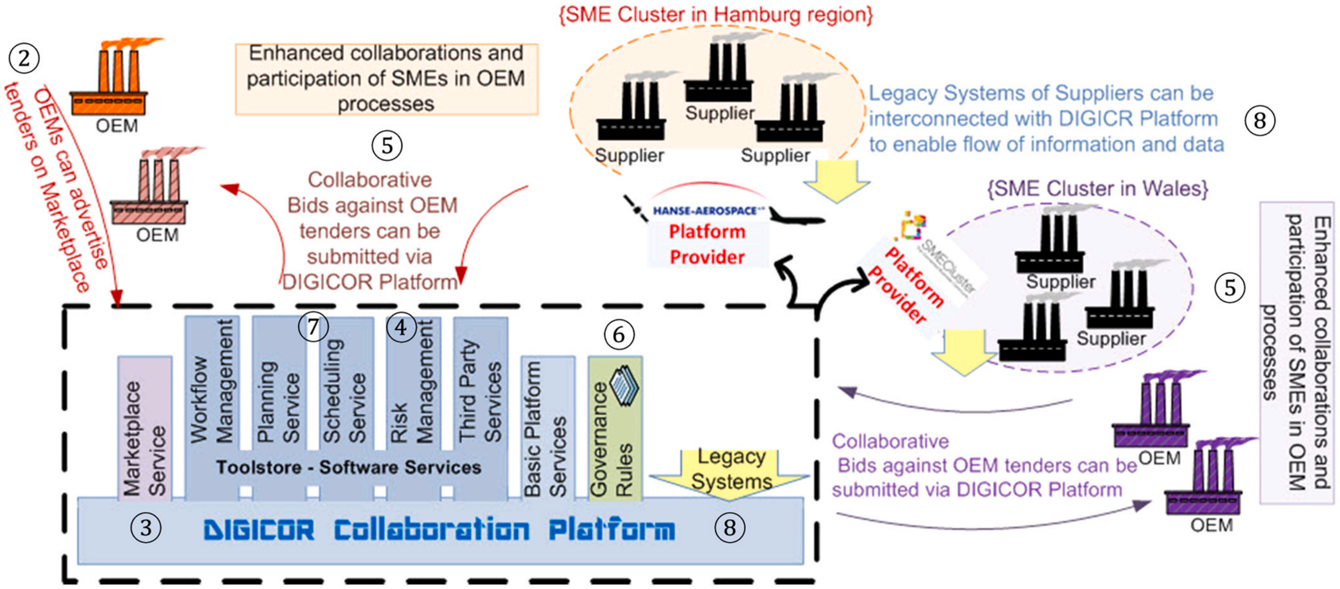


Fig. 3. Industrial context shaping the DIGICOR platform. Encircled numbers indicate mapping to the functionalities in Fig. 2.

of three years and involved collaboration among 11 European partners based in the Czech Republic, Germany, Greece, Italy, the Netherlands and the UK and representing universities, research organizations, OEMs, SME clusters, and software houses. Partners responsible for the development of platform services that closely interface with one other (Fig. 2) have been forming workgroups to coordinate specification of data exchange between the services and maintained regular communication. All-partner meetings have been held several times a year on sites of the project partners on the rotating basis, and project review meetings by the European Commission took place annually.

The above vision and industrial context of DIGICOR, along with the gaps and comparative analysis of literature presented in Section 2 envision the requirements for collaborative platforms in the context of I4.0. To sum up, the platform was designed to enable companies to create and operate collaborative networks across the supply chain (Koleva, 2018; Ferreira et al., 2016; Dallasega et al., 2018). The key advantages of using a collaboration platform approach underpinned by the I4.0 paradigm includes the possibility to (1) create a marketplace for B2B collaborations between SMEs, (2) include tools for planning and controlling collaborative production and logistics, (3) provide solutions for risk management, (4) support third parties to add services for advanced analytics, simulation or optimization via Application Programming Interfaces (APIs), and (5) enable seamless connectivity based on smart objects and real-time data sources in terms of IoT. These requirements motivate the proposed DIGICOR architecture and platform. In Table 4, we summarize the gap analysis of extant research in supply-chain collaborations between SMEs. Table 4 further presents the functional requirements for the DIGICOR platform addressing the identified gaps. Table 5 outlines non-functional requirements.

4.2. Architecture approach

To develop the architecture and the platform, we have considered the requirements of OEMs and SMEs from automotive and aerospace industries. The platform is designed to enable flexibility and simple integration of companies by using an EDSOA (Laliwala and Chaudhary, 2008) and middleware for interoperability and communication. Commonly, SOA's communication between services involves simple data passing or provision of additional services that coordinate connectivity between all components over a network. In contrast, a service in EDSOA has the capability to react to events and publish its own events as well — to let other services update their data accordingly. Each significant change in the state of a service is accompanied by publishing an event which describes the state change. To ensure performance and simplicity, EDSOA uses asynchronous messaging to exchange events. Key properties of event-based communication are that the event producer does not need to know who listens to the events, and it is the responsibility of event consumers to subscribe to particular event types. These properties promote loose coupling between services. Events can be delivered over HTTP by using standards like Web Services Reliable Messaging, Message Queues or Java Messaging Services (Hauser et al., 2010).

Fig. 4 illustrates the conceptual architecture of the DIGICOR platform. Three main mechanisms are used for component communication: REST services over HTTP(S) (Juneau, 2018; Pautasso et al., 2008), OPC Unified Architecture (OPC UA), and Advanced Message Queuing protocol (AMQP). Details on these are provided in Section 5.2. Our architecture approach and platform have a significant impact on facilitating participation of SMEs in digital manufacturing. Analysis of existing platforms and technologies in Section 2 reveals that current systems do not have effective mechanisms for supporting SMEs in forming partnerships. Instead, these systems rely on vertically integrated I4.0 adoption models and deliver a lower level of agility and product personalization. To support the realization of the I4.0 vision of supply networks, our proposed architecture and platform addresses these gaps and supports collaborations from setup to termination while integrating technological means in an open and flexible manner.

5. Architecture components

This section introduces the proposed DIGICOR architecture components. Collaboration of companies involves vertical and horizontal integration including production data and events from the

Table 4
Summary of gap analysis of extant research in supply-chain collaborations between SMEs and functional requirements for the DIGICOR platform.

Category	Identified Gaps	Functional Requirements for DIGICOR
System functionality and context	Current SME collaboration platforms such as “InteliGrid” (Dolenc et al., 2007) support only sharing of information but there is lack of models for recommending formation of a virtual enterprise (VE) and supporting its creation on digital platforms. There is also no way to evaluate potential suppliers to form a VE.	Recommendation for VE formation, support for VE creation, evaluation of potential suppliers to form a VE, management as if participants were a single company.
Logistics management	Logistics management, including delivery details, is approached separately, outside the digital platforms, or even without IT interaction.	Availability of capacity planners, contract support, production planners, operational and delivery tools, with resilient, scalable, automated solutions.
Monitoring	Monitoring is carried out mainly by manual updates. No IoT for supply chain monitoring is available integrated within a collaboration platform.	Real-time monitoring with connection to physical items, such as sensors and programmable logic controllers.
Risk evaluation	Risk evaluation, if any, is usually done outside digital platforms, using separate technological tools.	Risk evaluation will be an inherent and automated function of SCM.
Tools store	The tools store for SCM, ideally with third parties’ participation, is not supported, and normally third-party collaboration is not supported outside the role of being only a sales partner.	Third-party developers will be able to provide useful tools for the platform to support SCM.
SME cluster support	No existing platform support for SME clusters; no state-of-the-art architecture meeting all requirements indicated in Tables 4 and 5.	An ecosystem is required for SME clusters. A novel architecture combining advantages of microservices and event-based architectures is supposed to be designed to support building of the ecosystem.

shop floor, which may require integration of factories with different levels of automation. Production events must be easily shared among collaboration partners and hidden from other companies. As collaborations may take place over a certain period, and new collaborations may emerge, the platform needs to ensure scalability given the numbers of potential collaborations and companies involved.

In response to the requirements (Section 4.1), and building on the properties of EDSOA, the proposed architecture features a specialized EDSOA. Moreover, the proposed architecture adds to EDSOA mechanisms for modular and efficient communication through semantically defined messages. These allows entities in the platform (i) to easily share complex information about the offered and requested capabilities, products, and services, and further data about the current state of collaboration between two or more entities; (ii) to formulate new vocabularies needed to capture new business opportunities and models of collaboration including shared understanding of collaborative processes.

In Section 5.1 we present the DIGICOR’s component model. Section 5.2 outlines components interaction and deployment. The factory connectivity architecture is introduced in Section 5.3. Section 5.4 describes semantic models used in the architecture. A proof-of-concept implementation of the platform architecture is discussed in Section 5.5.

5.1. Components specification

Based on the architectural overview (Fig. 4), we present main components in Fig. 5 and describe them below.

1) **Company Node** represents the company infrastructure on the platform. Each Company Node comprises several core services and tools, including Company Node Management Service, Tool Installer, Security Service, a connector to Collaboration Nodes, Tool Store, Marketplace and Factory Connectors (see below), and

Table 5
DIGICOR platform system scope and non-functional requirements.

Requirement	Description / Rationale
System functionality scope	The platform facilitates automation of supply chain collaborations, provides tools and services for companies to improve information visibility, and provides collaboration process support including access to shop floor data.
Usability and interfaces	The platform provides a suitable interface for users to access services during the collaboration phase. Furthermore, it interacts with manufacturing execution and management information systems to gain access to the relevant data.
Performance and scalability	The platform is expected to adequately handle workload compatible with industry benchmarks for B2B platforms, with the platform capable of scaling towards serving thousands of collaborations involving several thousands of companies in the supply chain.
Security, knowledge protection and governance	The platform incorporates effective security mechanisms as an integral part of its core architectural layers, ensuring data protection and resource access control through: 1) Administration of access and usage control rules on collaborative resources (Policy Engine). 2) Specification and enforcement of digital governance rules and procedures. 3) Binding of policies to the content (MPEG-M Engine). 4) Multi-level security with encryption both in transit and at rest (Crypto Engine). 5) Secure execution of collaborative document management workflows (Content Engine).
Flexibility, scalability, innovation	The architectural style should create an open platform that accommodates various types of end-users and B2B collaborative processes, providing a framework for collaboration rather than imposing specific processes or collaboration patterns.
Digital transformation and SME marketplace creation	The platform can be hosted by SME clusters that facilitate connection of collaboration partners to OEMs’ SCM systems. It provides collaboration services and tools for planning and controlling of production locally and across the network. Seamless integration of cyber-physical systems should also be supported.
Semantic technologies for interoperability and tool integration	The platform fulfills a need of efficient communication among all entities acting in the market, which relates to ease of sharing complex information in the platform, and the use of semantic technologies (STs) to address this objective. The STs should also facilitate tool integration supporting various aspects of manufacturing from different application domains.

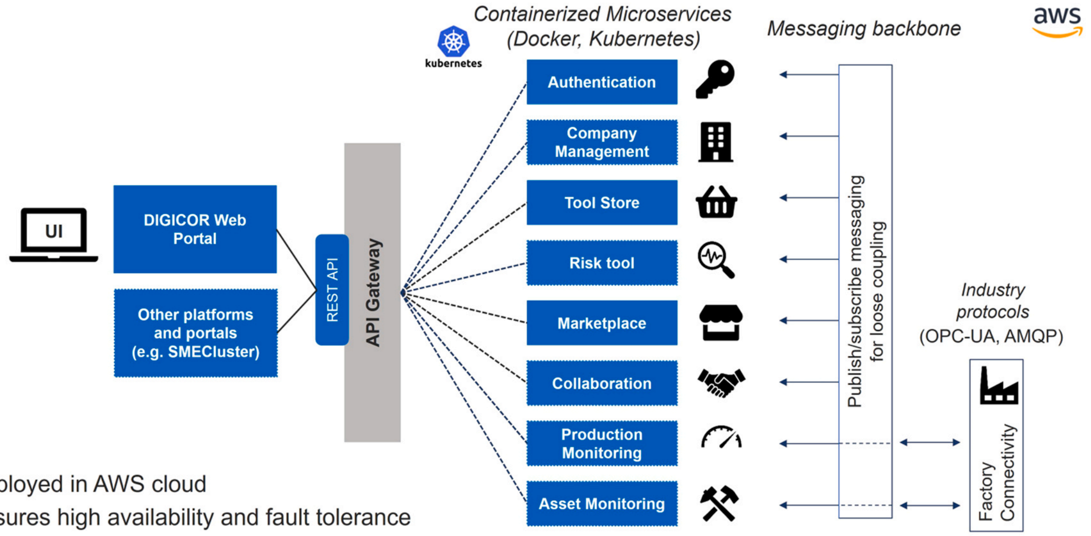
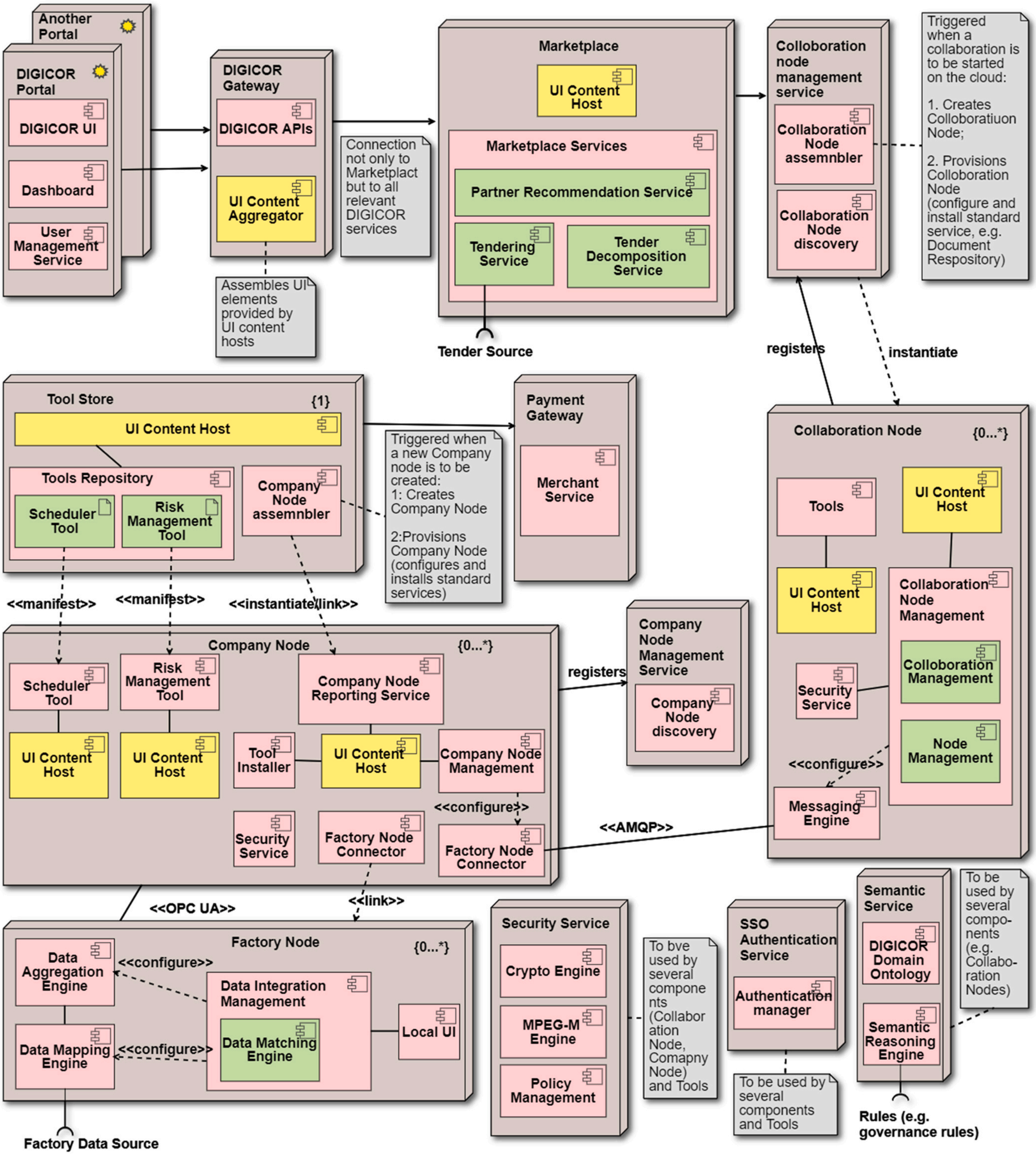


Fig. 4. Conceptual architecture of the DIGICOR platform.

a service discovery tool. The Company Node is created when the company is registered on the platform and starts using services. Company Node Management Service administers the Company Node and controls its lifecycle and collaborations.

2) **Collaboration Node** is a mediator enabling communication between Company Nodes that represents companies belonging to the same consortium while preventing unauthorized access to data from outside the consortium. Therefore, the Collaboration Node plays an important security role and enforces governance rules. In addition, collaborative Tools from the Tool Store can be installed in a Collaboration Node offering functionalities for all partners within the collaboration, such as document repositories, project management tool, and negotiation tools. The Collaboration Node Management Service concerns the management of a collaboration, in the sense of a business contract, from the moment the collaboration begins until its final resolution.
3) **Factory Node** is responsible for connecting legacy factory systems owned by the collaborating partners with the platform. It uses the OPC UA protocol for sending production data and events to the corresponding Company Node. The complexity of the Factory Node's internal structure depends on the level of automation in the factory infrastructure. As companies may have multiple factories, several Factory Nodes can be connected to the Company Node. Through Factory Nodes, the production monitoring service provided by the DIGICOR operative tools could orchestrate the production process within a consortium of companies. The Factory Node interface is described in Section 5.3.
4) **Tools** provide functionalities and services to Company Nodes and Collaborations Nodes. The concept of Tools allows configuration of Company Nodes according to the users' needs and enables platform versatility. Each company may install a set of Tools in the Company Node. The DIGICOR platform readily offers a selection of Tools, such as the Risk Management Tool and the Scheduler Tool.
5) **Tool Store** serves as a central Tool distribution center for the platform. It allows users to download and instantiate tools into their platform infrastructure. The Tool Store is implemented as a separate service accessible through the REST API. It keeps the database of Tools and assists in the creation of Company Nodes. Only Tools from the Tool Store can be instantiated into the platform infrastructure.
6) **Marketplace** supports the tendering process required for the platform to be operational and participates in the instantiation of the Collaboration Node by providing the collaboration profile to the Collaboration Node Management Service. It contains the following services: (1) Tendering Service for posting a call-for-tenders and responding to such calls; (2) Tender Decomposition Service to enable decomposition of a tender into products and/or services; and (3) Matchmaking Service for searching for potential suppliers and partners to form a consortium. These services are detailed in Section 6.2.
7) **DIGICOR Portal** represents a front-end where the interaction of users with the platform takes place. The Portal provides user management for the platform. An integral part of the Portal is a dashboard where user interfaces (UIs) of all tools installed in the platform infrastructure are presented. The Portal does not request data from individual services but does so instead from the DIGICOR Gateway.
8) **DIGICOR Gateway** is the main entry point of the platform. Its purpose is to provide APIs for clients requesting platform services. It exposes REST APIs and calls downstream services (Marketplace, Tools, etc.) to deliver requested data to the client. The APIs offer access to selected services and the UI mashup to be presented in the Portal. In addition, the Gateway is a central point where authentication of incoming requests is performed. Therefore, access to platform services by external portals (such as SME cluster portals) is possible through the Gateway. This is how we specialize the EDSOA to enable flexibility and simple integration of companies. This is also the main difference to normal EDSOA which uses a single sign-on technology to only allow an internal user to access the data and services (Hauser et al., 2010). In comparison, the DIGICOR platform becomes a dynamic ecosystem that benefits from an entry point where services can be consumed by external clients, such as portals.
9) **Supporting services**, such as the Authentication Service, Company Node Management Service and Asset Monitoring Service, ensure proper functioning of the platform.



Connection not only to Marketplact but to all relevant DIGICOR services

Assembles UI elements provided by UI content hosts

Triggered when a collaboration is to be started on the cloud:

1. Creates Colloboratiuon Node;

2. Provisions Colloboration Node (configure and install standard service, e.g. Document Respository)

Triggered when a new Company node is to be created:
1: Creates Company Node

2:Provisions Company Node (configures and installs standard services)

To bve used by several components (Collaboration Node, Comapny Node) and Tools

To be used by several components and Tools

To be used by several components (e.g. Collaboration Nodes)

Fig. 5. DIGICOR's component model.

5.2. Components interaction and deployment

This section outlines the three main mechanisms for components communication on DIGICOR platform: REST services, OPC UA and AMQP. Most of the services on the platform have REST endpoints providing access to various functionalities. The main communication protocol between the Factory Node and the Company Node is the OPC UA which is a machine-to-machine communication protocol for industrial automation (OPC foundation, 2020). Automated and configurable exchange of production events can be enabled by the

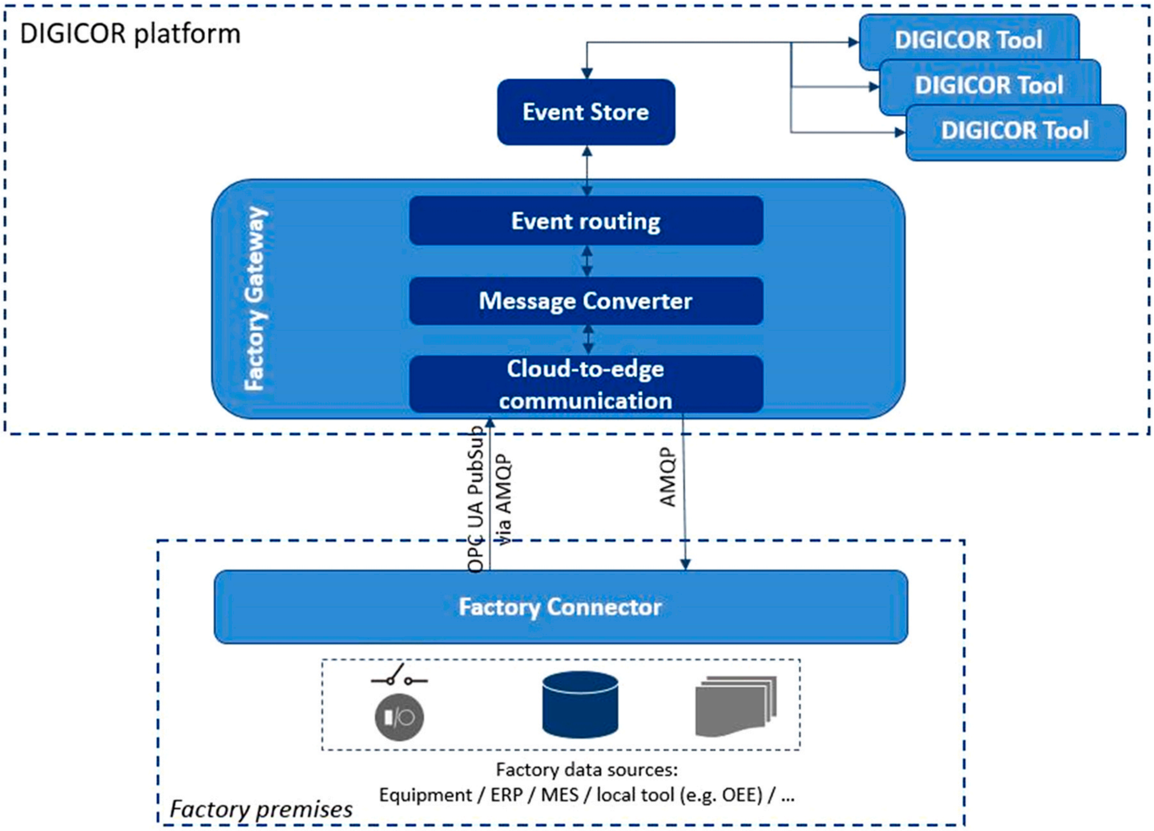


Fig. 6. The DIGICOR factory connectivity architectural pattern.

server and clients in OPC UA between both nodes (Hannelius et al., 2008). AMQP plays a central role in DIGICOR as it is used for distributing all production events on the platform. This is an open standard application layer protocol for message-oriented middleware (Luzuriaga et al., 2015). Content-aware AMQP routers are used inside Company Nodes and Collaboration Nodes to route messages inside and between Company Nodes, respectively.

In the design of the platform, we structure the DIGICOR components as a logical group of services isolated by restricted network access rather than a physical entity. To achieve this, the core DIGICOR components are deployed in isolated Docker containers. The Docker container technology has been chosen as it offers functionalities superior to its competitors (Preeth et al., 2015).

To enable access for all companies regardless of their IT infrastructure, the DIGICOR platform offers possibilities to run in the cloud, providing services in the SaaS fashion. A public cloud (Amazon Web Services) was used in our deployment. The primary advantage of a public cloud is that it offers many required infrastructure services, such as load balancers and service discovery, promoting agile development.

5.3. *Factory connectivity*

Manufacturing operations involve collaborative networks, hence the need for coordinating and monitoring of production processes among the involved companies is paramount. Establishing information exchange among the parties' automation systems necessitates connectivity and interoperability between heterogeneous systems. Therefore, seamless connectivity to automation solutions, smart objects and real-time data sources, is one of the most important goals of our architecture and the DIGICOR platform. The factory connectivity architecture complements and extends the platform architecture, supporting seamless connectivity to factory systems and reliable connection between them and the platform. It has two main building blocks: the Factory Gateway (located within the DIGICOR platform) and the Factory Connector (located on-premises), as illustrated in Fig. 6 and explained below (Bnouhanna and Neugschwandtner, 2019).

Factory Gateway manages information exchange between Factory Connectors and the DIGICOR platform. It connects to the Factory Twin, which is part of the Factory Connector, and translates the Factory Twin's OPC UA information model to DIGICOR events, which it forwards to other DIGICOR tools and services via the Eventuate client (and vice versa). On the one hand, the Factory Gateway communicates like other DIGICOR tools by publishing and subscribing to application events; on the other hand, it receives OPC UA Publish/Subscribe (PubSub) messages from the Factory Connector. Each message received from a Tool or the Factory Connector is converted to the appropriate representation and then routed either to the corresponding Factory Connector or the suitable tool.

Factory Connector manages the connection with local data sources and provides mapping and aggregation services to offer interoperability between the local sources and the DIGICOR production data model. The Factory Gateway, as shown in Fig. 6, is composed of a cloud-to-edge communication component which is an OPC UA subscriber in charge of receiving messages from the Factory Connector using OPC UA PubSub over AMQP, and an AMQP publisher that sends messages to the corresponding Factory Connector. The message converter component is responsible for translating the OPC UA Published DataSet to DIGICOR events and vice versa. Event routing consumes and publishes events from/to the Event Store. Alongside the above functionalities, the Factory Gateway is also responsible for breaking down the collaboration plan into collaborating partners' sub-plans which are then routed to their respective Factory Connectors. The Factory Gateway also acts as an intermediary in the negotiation of the data to be exchanged between the Factory Connector and DIGICOR tools.

Three phases can be identified in establishing and keeping connectivity between DIGICOR tools and data sources at a factory: **(1) Installation:** a Factory Connector is pre-configured for on-premise installation and enabled to connect to the Factory Gateway. **(2) Configuration:** the first aspect of this phase is the negotiation of requests for factory data made by DIGICOR tools, and the second is the data collection and preprocessing at the Factory Connector level. In our work, the focus is on the first one. **(3) Data transfer:** production data updates are published to DIGICOR tools.

To summarize, Factory Connectors enable connectivity and semantic interoperability between the local factory data sources and the Factory Gateway. Further, the Factory Gateway is a core component of the DIGICOR middleware that enables interoperability and connectivity between Factory Connectors and DIGICOR tools and services responsible for monitoring and synchronizing the collaborative manufacturing process.

5.4. DIGICOR ontology layers

The requirements of the DIGICOR platform presented in Sections 4.1 and 5.3 envision a need for an efficient communication mechanism among the involved entities, which relates to ease of sharing complex information. Therefore, the use of semantic modelling tools to address this objective is a cornerstone of the DIGICOR architecture. To this end, domain ontologies provide a flexible data modelling solution capable of capturing all aspects of supply chain collaborations (Chandra and Tumanyan, 2007; Zdravković et al., 2011; Ye et al., 2008). An essential task in any intelligent system is expressing, processing and sharing knowledge. In the field of semantic technologies, the term 'ontology' is commonly defined as an "explicit specification of conceptualization" (Lee et al., 2006). Using the domain knowledge encoded in these conceptualizations and in the relationships between them, a system based on our architecture can exchange information between distributed modules which is sufficiently rich with domain knowledge to perform logical inferences supporting matchmaking and team composition services.

However, the idea of mandating a semantics-rich ontology language for communication between all modules in the system goes ahead against principles of modular development, since it would presume ontology skills amongst all developers of modules within the architecture, and create "by stealth" a tighter coupling between these modules because of the rudimentary state of standardization of the ontology description and communication languages. The architectural innovation embraced to resolve this contradiction focuses on two communication levels between modules in the system:

1) The lower level is used for communication between all modules in the system with a comparatively simple JSON encoding used as "payload" within event-based inter-module communications. Within modules which do not need to operate with an ontology, these JSON encoded objects are converted to Java Objects and processed and stored accordingly.
2) The higher level, whilst still using JSON encoding, also links the exchanged entities with concepts within a shared ontology. The full semantics including multiple inheritance and axioms can thus be recovered and used to conduct non-trivial reasoning based on knowledge encoded in the ontology.

Using this two-tier solution, we can restrict the need for ontology expertise to modules which can make use of the rich domain dependencies encoded within the ontology, and use JSON — a widely accepted data encoding format for simple textual communications between modules which do not depend on ontological knowledge for their operation.

We use similar layering within the ontologies used to ensure semantic interoperability to the degree needed by individual modules. Within the semantic layers, we rely on standards based on Semantic Web technologies.[2] The most abstract semantics layer understood by all modules is the DIGICOR Core Ontology (DCO) based on the DOLCE foundational ontology, the latter chosen because of its coverage of core domain constructs needed in the engineering of the platform (Jirkovský, 2019). DOLCE is a part of the WonderWeb library of foundational ontologies used in domains ranging from law to agriculture (Oberle et al., 2007; Gangemi et al., 2005).

The DIGICOR collaboration ontology (Kazantsev et al., 2018) resides on top of the DCO and is designed to represent finer details of knowledge regarding computer-supported inter-company collaboration in the supply chain context, defining core concepts such as goal and goal requirements, company characteristics and responsibilities, and processes for operationalizing goals. The links between them allow guiding of goal decomposition and matchmaking between company capabilities and goal requirements in response to a call-for-tenders (Pishchulov et al., 2019).

The results of decomposition and matchmaking are recorded in a model establishing the collaboration between the companies. Once a company has been assigned a responsibility for a sub-goal, it can choose how to operationalize it with a process. The process concept and the standard top-level process decomposition is based on the Supply Chain Operations Reference (SCOR)[3] model and Design Chain Operations Reference (DCOR) (APICS, 2013) models. The collaboration ontology has been designed so that domain-based ontologies can be extended from it. It meets the needs of the platform services, such as the Tender Decomposition and Matchmaking Service (Cisneros-Cabrera et al., 2021) (see Section 6.1.2).

5.5. DIGICOR technical infrastructure implementations

To test and validate the proposed architecture of the DIGICOR platform, a proof-of-concept prototype was implemented and successfully presented by the DIGICOR project partners to prospective users. The prototype demonstrated core functionalities and tested some technologies suitable for the implementation. The following functionalities are incorporated into this prototype:

1) Setting up a Company Node and provisioning services selected by a user;
2) Making the Company Node available for the user;
3) Creating a collaboration between companies;
4) Demonstrating functional collaboration on communication between both Company Nodes.

The following technologies have been used in the implementation: Docker, ActiveMQ[4] and Angular JS.[5] The physical setup of the application prototype consisted of two computers connected by a

---

[2] https://www.w3.org/standards/semanticweb/

[3] http://www.apics.org/apics-for-business/frameworks/scor

[4] http://activemq.apache.org

[5] https://angularjs.org/

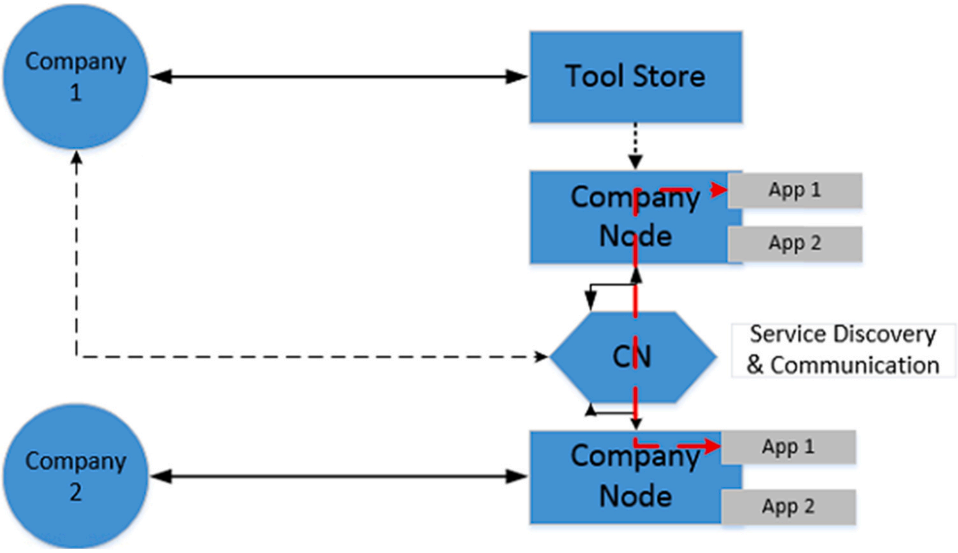


Fig. 7. Demo communication flow chart.

network, each running an instance of the Docker daemon, serving as a host of a Company Node.

The implemented scenario is the user, representing a company, creating a Company Node by selecting several services from the Tool Store. After that, the user accessed the companies list and created a collaboration with one of the available companies. When the collaboration was created, the corresponding event was published. This event notified the respective companies and enabled their communication via the Collaboration Node. The production scenario was simulated by simplified demand and supply services in each Company Node. In the Company Node UI, the user could place an order with another company and then receive the production events with delivery progress. The demo prototype communication flow chart is shown in Fig. 7. The prototype demonstrated the implementation and deployment of portions of the functionality of the DIGICOR platform and successfully tested the technologies used.

5.6. Performance and scalability

One of the requirements that had to be addressed when designing the DIGICOR architecture was its ability to scale up. Depending on the target environment, computing resources may vary considerably. For example, as more customers join the platform and several smart factories are connected, the demand for computing resources will grow gradually. However, predicting the pace of such growth is a challenging capacity planning undertake. This non-functional requirement has been addressed early on by deploying the DIGICOR platform into the Amazon Web Services (AWS) cloud.[6] AWS provides elastic services enabling scaling the platform up and down according to immediate needs. We used the following highly available AWS services:

1) **Amazon EC2.** Computing power that can easily be adjusted by properly selecting both the number and type of Amazon EC2 instances. A broad range of processors, storage, and networking options are available.
2) **API Gateway.** A broad dynamic range of calls can be controlled using AWS API Gateway accepting and processing up to hundreds of thousands of concurrent API calls including traffic management, authorization, and access control.
3) **Amazon RDS and Dynamo DB.** Managed database services providing both relational and NoSQL databases depending on the specific needs of customers.
4) **AWS Lambda.** Serverless, event-driven computing service enabling to run code on-demand in “pay for what you use” fashion, with a very fast code execution and controlling of costs.

With the help of the above-mentioned AWS services, the DIGICOR platform is capable to support heavy workloads with high availability levels and flexibility. It is a matter of cost optimization to choose the AWS performance tier that should be used for a given scenario. For testing purposes, even the AWS free tier can be used to run most of the platform services. However, for production use, paid tiers are naturally required. Comprehensive performance benchmarking and scalability stress testing is beyond the scope of this paper.

6. Scenario-based validation

The term ‘use case’ implies the way in which a user uses a system. It is a collection of possible sequences of interactions between the system under construction and its external actors, related to a particular goal (Ribu, 2001). Actors here are the users of the DIGICOR platform. In this section, we present some key use cases of the platform: how a user creates a call-for-tenders (CfT), how users identify the best fitting partner or a set of partners to jointly respond to a CfT and how the SCM collaboration is facilitated by the DIGICOR platform. This section also describes how platform components interact to support these use cases and how the platform implements key requirements by instantiating the designed architecture.

The users in two use cases of Section 6.1 demonstrated below are already registered in the platform. The service they interact with when registering is the membership management service. For brevity and focus, this and other pre-collaboration use cases are presented in (DIGICOR, 2019). Videos related to DIGICOR tools and use cases can also be viewed at https://www.digicor-project.eu/videos.

6.1. Use case: offer

This use case refers to the Marketplace part of the platform, describing OEM’s CfT and suppliers’ offer creation and submission. The OEM uses the Tendering Service to create a CfT and publish it on

---

[6] https://aws.amazon.com

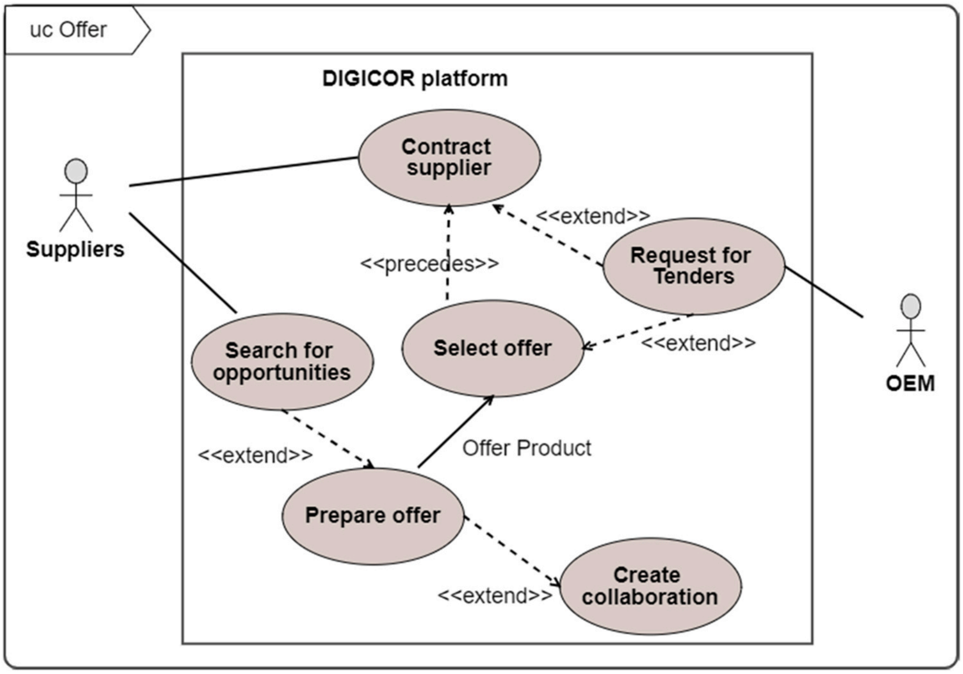


Fig. 8. Offer use case diagram.

the platform. When one of the companies registered on the platform finds or is notified about this CfT and wants to respond to it in collaboration with other companies — so as to jointly satisfy the CfT requirements, it calls the Tender Decomposition and Matchmaking Service to decompose the tender and receive a list of suppliers capable of fulfilling the tasks identified through the tender decomposition. This company is accordingly referred to as the Lead Supplier. Further, the Collaboration Service is invoked to request a collaboration with the identified suppliers. Once the collaboration is confirmed, potential partners start the creation of the consortium. After all consortium members are contracted, the resulting collaboration profile is sent to the Collaboration Node Management Service. Fig. 8 shows the use case diagram. In the following subsections, we detail the processes of creating a CfT and forming a consortium.

6.1.1. *Creating a CfT*

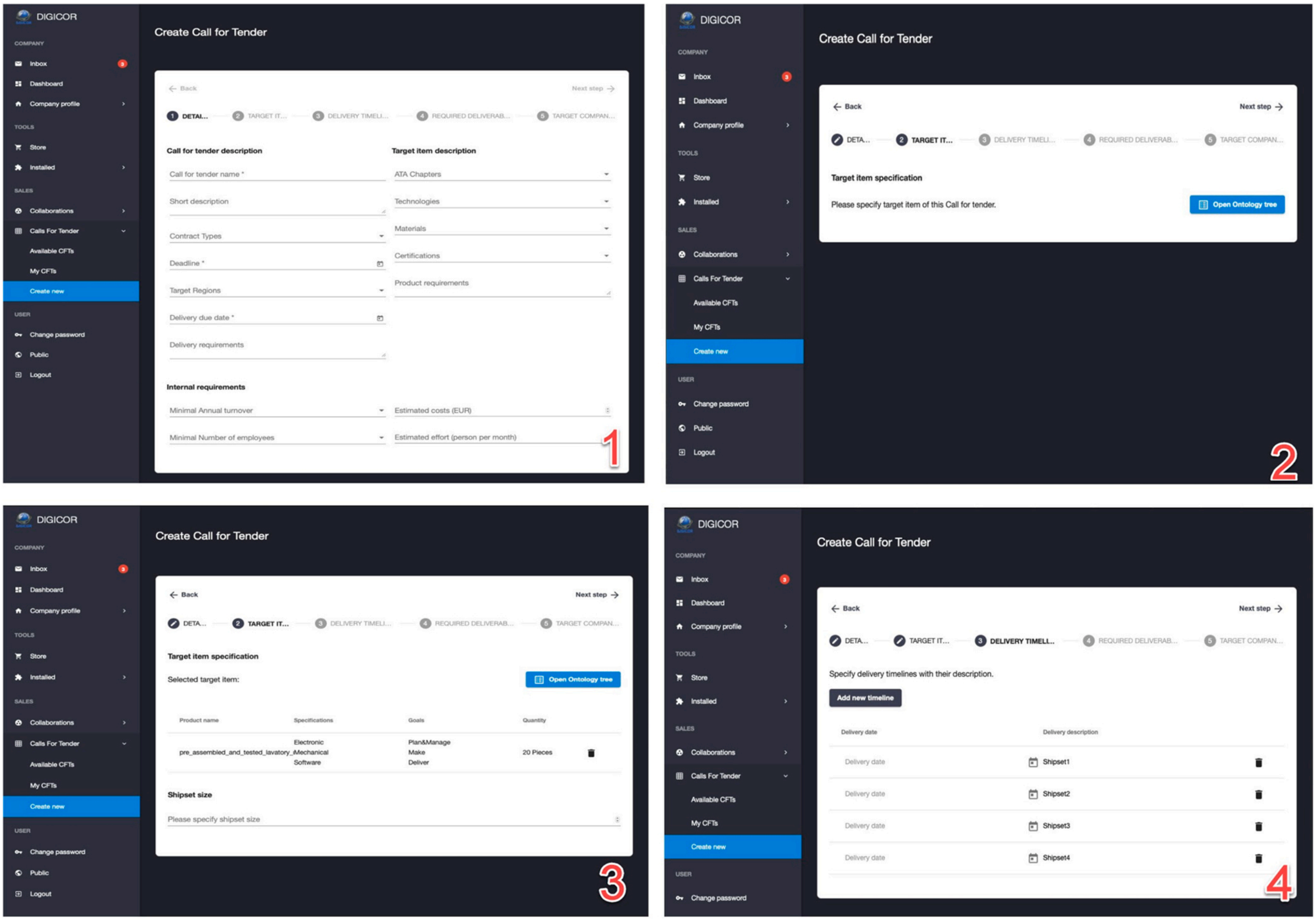
CfT creation consists of six steps. In the **first step** (Fig. 9-1), the user specifies the CfT description, the target item description, and internal requirements. The CfT description comprises a name, a short description, target geographic regions, contract types, tender submission deadline, delivery deadline, and delivery requirements. The target item description comprises the ATA Chapters, which is a common referencing standard for commercial aircraft documentation (ATA, 1999), technologies, materials, certifications, and product requirements. The internal requirements comprise the minimal annual turnover, minimal number of employees, estimated costs, and estimated effort in person-months. The **second** and **third steps** involve the target item specification (Fig. 9-2 and 9-3). Users can select a target item from the product ontology tree (Fig. 10) and set specifications, goals for the target item, and the quantity requested. They can then specify shipment sizes. The **fourth step** (Fig. 9-4) sets the delivery timeline for the target item. If the user specifies a shipment size then the delivery timeline is prepared automatically based on the requested quantity. For each delivery, the user should specify a date and a description. The **fifth step** of CfT creation is the required deliverables specification (Fig. 11–5), which is necessary for collaboration flow. The **last step** is the target company selection (Fig. 11-6), where the user can specify which companies can view the CfT.

6.1.2. *Applying for a CfT*

The *Available Calls for tenders* screen contains a list of CfTs visible to the user's company (Fig. 12–1). The user may view a specific CfT by selecting it from the list. The *Call for tender details* screen (Fig. 12–2) displays basic information about the CfT: product name, description, CfT creation date, due date, contract types, target regions, and the required certificates, materials and technologies. If any of these items are blank, it means that the CfT creator did not specify them. The bottom part of the screen presents the target item requested in the CfT: its name, specifications, goals and requested quantity. This screen also provides access to the target item's product structure via the *Open target item tree* button.

Pressing the *Apply* button will navigate the user to 'Apply for call for tender' screen. When responding to a CfT, companies can form collaborations, ensuring they collectively meet the CfT requirements. This functionality is provided by the Tender Decomposition and Matchmaking Service (TDMS). TDMS allows tender decomposition and matching of individual tasks to available suppliers, which helps to identify the best fitting partner or a set of partners (a *team*) for the given CfT.

The TDMS UI divides the interaction with the user into three screens according to the following workflow: (1) Search prospective teams, (2) Review teams & replace members, and (3) Review assignments. Fig. 13 shows the first screen of the TDMS UI.



Please specify target item of this Call for tender.

Product name	Specifications	Goals	Quantity
pre_assembled_and_tested_lavatory_	Electronic Mechanical Software	Plan&Manage Make Deliver	20 Pieces

Specify delivery timelines with their description.

Delivery date	Delivery description
Delivery date	Shipset1
Delivery date	Shipset2
Delivery date	Shipset3
Delivery date	Shipset4

Fig. 9. Creating a CfT – Steps 1 to 4.

The user can execute matchmaking for the entire product or its individual parts and thus build the team incrementally. When a specific element is selected by the user in the product structure of the TDMS UI, matchmaking will be executed for that item, and otherwise for the target item (top node of the product structure). In the former case, the goals for the item are derived from the goals specified in the CfT for the target item, through their decomposition. The user will be alerted if none of these permit decomposition (such as Deliver). The search for prospective teams is executed by pressing the button *Search for teams*.

Fig. 14 illustrates the search results presented to the user in the second screen: *Review teams & replace members*. Since a part of the target item has been selected in Fig. 13, the search for prospective teams has been executed solely for that part, called *lavatory_door_module1*. The goals for it are derived from the goals for the target item *pre_assembled_and_tested_lavatory_module_1*: Design & Develop, and Make. Their decomposition implies the following goals for *lavatory_door_module1*: Design & Develop, Make, Deliver. As the figure shows, the search results contain a single prospective team. They show allocation of tasks within the team in a tabular form,

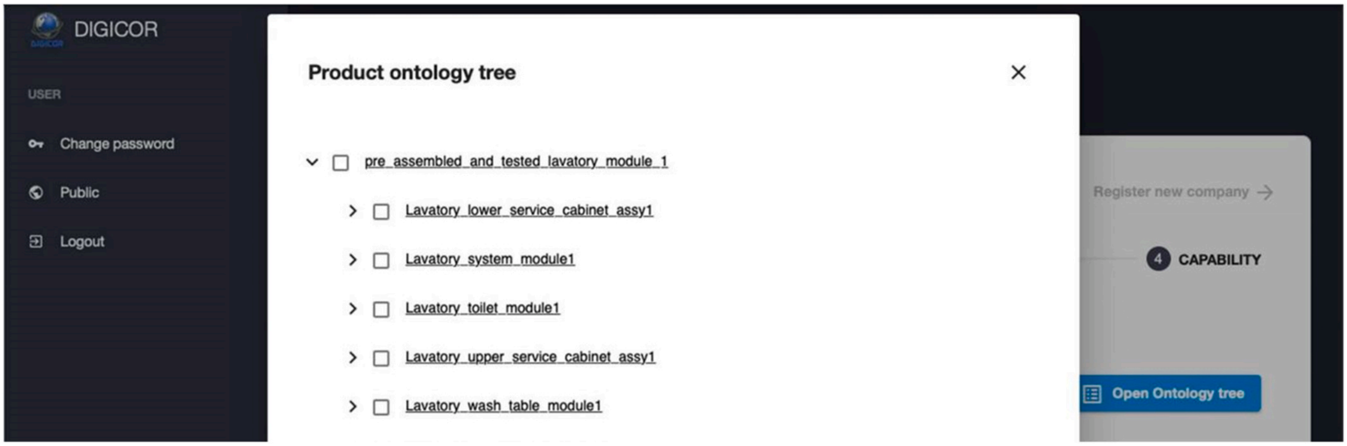
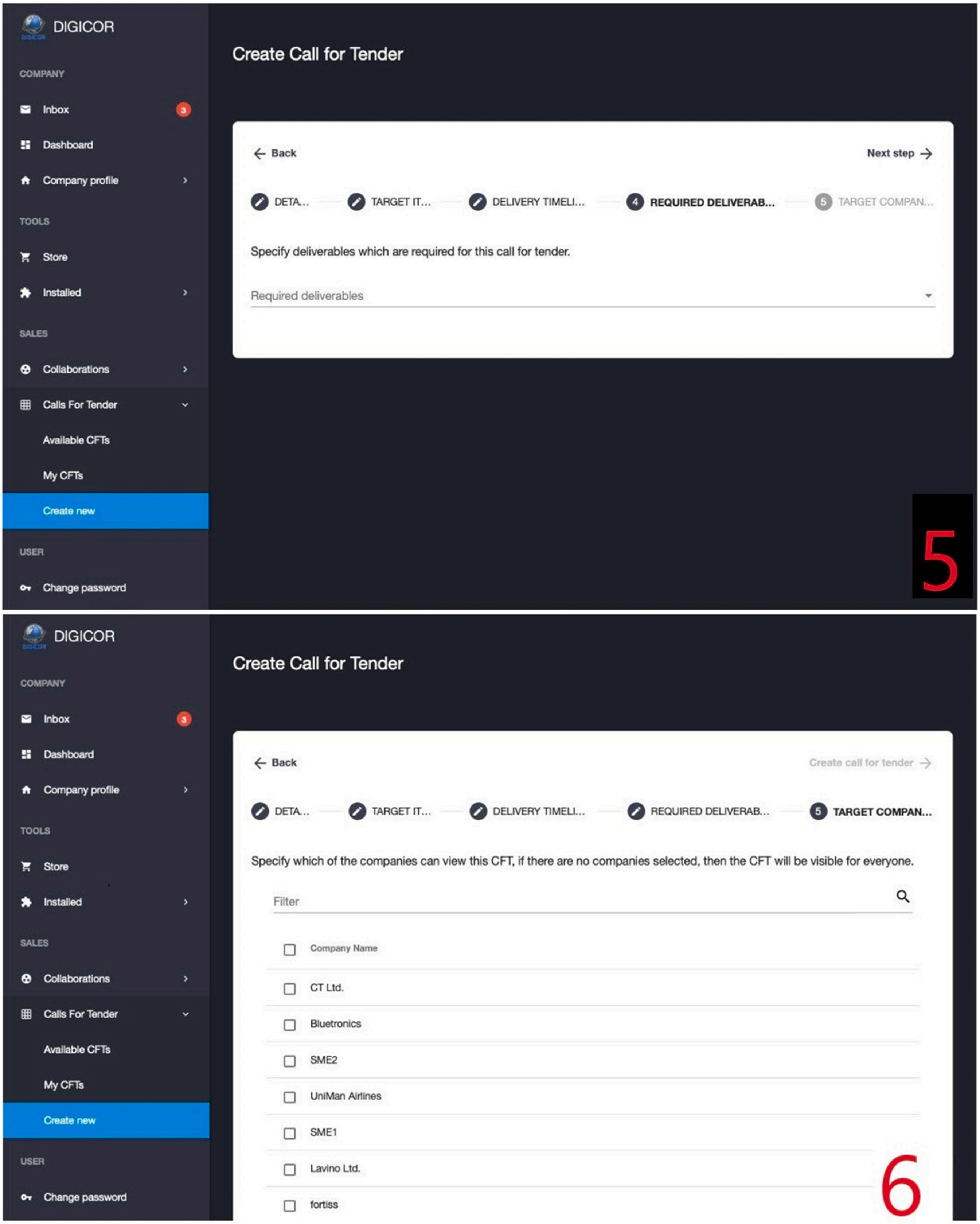


Fig. 10. Example of a product ontology tree.



Create Call for Tender

Specify deliverables which are required for this call for tender.

Required deliverables

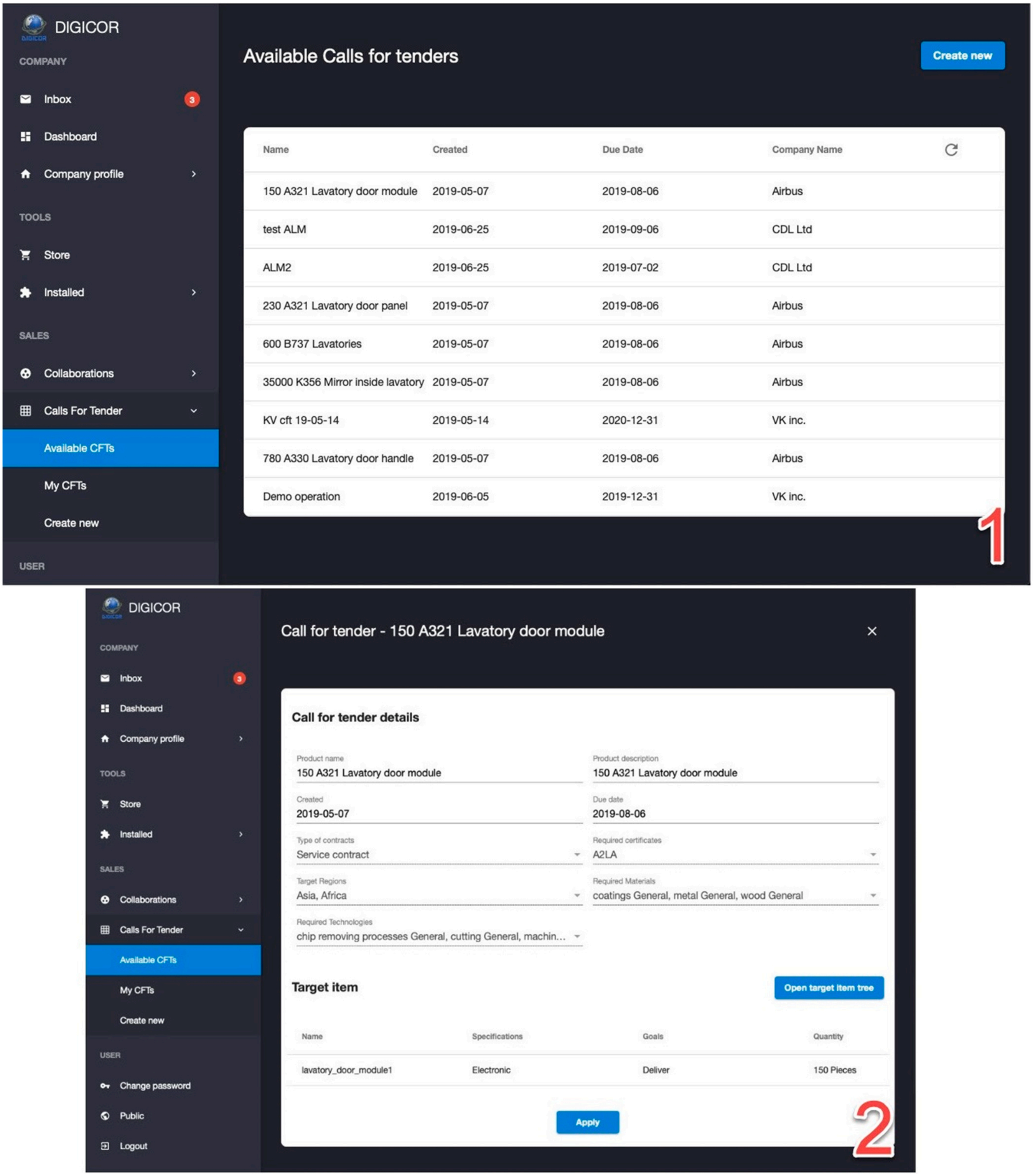
Create Call for Tender

Specify which of the companies can view this CFT, if there are no companies selected, then the CFT will be visible for everyone.

Filter

☐ Company Name
☐ CT Ltd.
☐ Bluetronics
☐ SME2
☐ UniMan Airlines
☐ SME1
☐ Lavino Ltd.
☐ fortiss

Fig. 11. Creating a CfT – Steps 5 and 6.



Available Calls for tenders

Name	Created	Due Date	Company Name
150 A321 Lavatory door module	2019-05-07	2019-08-06	Airbus
test ALM	2019-06-25	2019-09-06	CDL Ltd
ALM2	2019-06-25	2019-07-02	CDL Ltd
230 A321 Lavatory door panel	2019-05-07	2019-08-06	Airbus
600 B737 Lavatories	2019-05-07	2019-08-06	Airbus
35000 K356 Mirror inside lavatory	2019-05-07	2019-08-06	Airbus
KV cft 19-05-14	2019-05-14	2020-12-31	VK inc.
780 A330 Lavatory door handle	2019-05-07	2019-08-06	Airbus
Demo operation	2019-06-05	2019-12-31	VK inc.

Call for tender - 150 A321 Lavatory door module

Call for tender details

Product name: 150 A321 Lavatory door module
Product description: 150 A321 Lavatory door module
Created: 2019-05-07
Due date: 2019-08-06
Type of contracts: Service contract
Required certificates: A2LA
Target Regions: Asia, Africa
Required Materials: coatings General, metal General, wood General
Required Technologies: chip removing processes General, cutting General, machin...

Target item

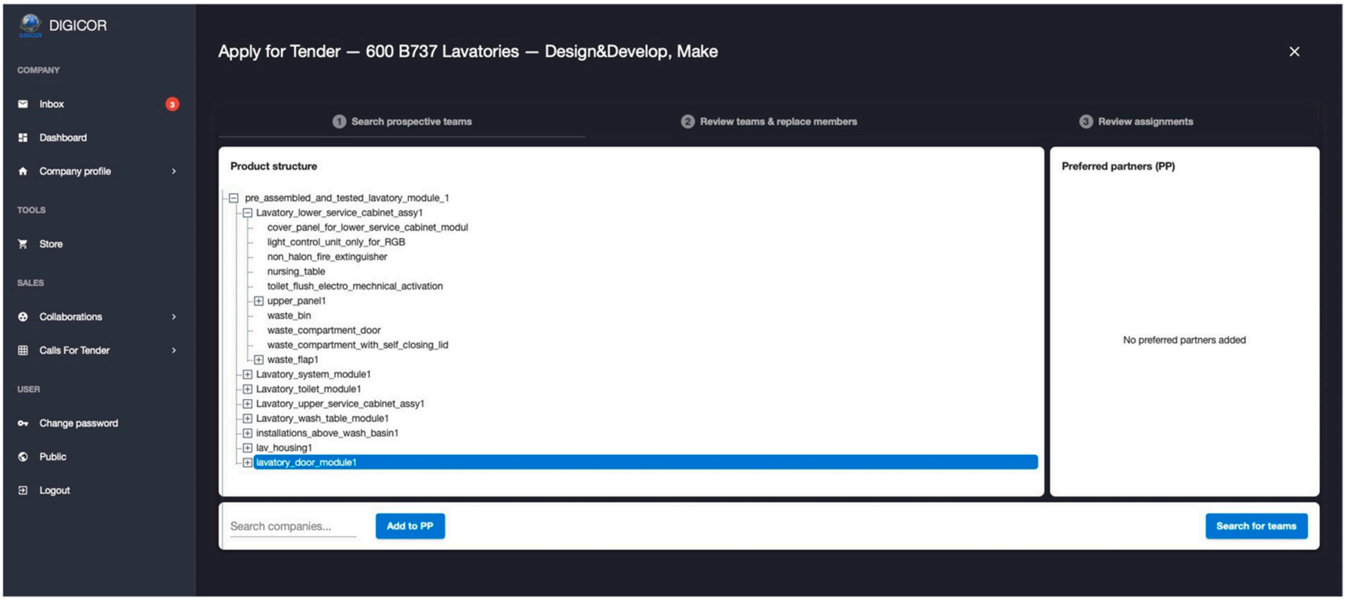
Name	Specifications	Goals	Quantity
lavatory_door_module1	Electronic	Deliver	150 Pieces

Fig. 12. Available Calls for tenders and Call for tender details screens.

where each row of the table indicates a company, an item, and the goals associated with that item. Hence the same company may be assigned to deal with several items.

Fig. 15–1 and 15–2 show an example of replacing team members in the TDMS UI. If the user wishes to replace a team member on a particular item, they can tick the checkbox in the *Replace* column and press the *Replace* button (Fig. 15–1). TDMS then looks for alternative sub-teams that can fulfil the goals for the given item and will automatically pick one with the highest team fit. As in the case of the initial team search, prospective sub-teams may consist of a single company. If the search succeeds, the selected company–item combination is replaced with the new sub-team (Fig. 15–2). The user can select several company–item combinations for replacement at once and can also specify preferred replacements.

Each time the user clicks on the *Assign* button in the second screen of the TDMS UI (Fig. 15–2), the ticked tasks become assigned



Apply for Tender — 600 B737 Lavatories — Design&Develop, Make

Product structure

- ⊟ pre_assembled_and_tested_lavatory_module_1
  - ⊟ Lavatory_lower_service_cabinet_assy1
    - cover_panel_for_lower_service_cabinet_modul
    - light_control_unit_only_for_RGB
    - non_halon_fire_extinguisher
    - nursing_table
    - toilet_flush_electro_mechnical_activation
    - ⊞ upper_panel1
    - waste_bin
    - waste_compartment_door
    - waste_compartment_with_self_closing_lid
    - ⊞ waste_flap1
  - ⊞ Lavatory_system_module1
  - ⊞ Lavatory_toilet_module1
  - ⊞ Lavatory_upper_service_cabinet_assy1
  - ⊞ Lavatory_wash_table_module1
  - ⊞ installations_above_wash_basin1
  - ⊞ lav_housing1
  - ⊞ lavatory_door_module1

Preferred partners (PP)

No preferred partners added

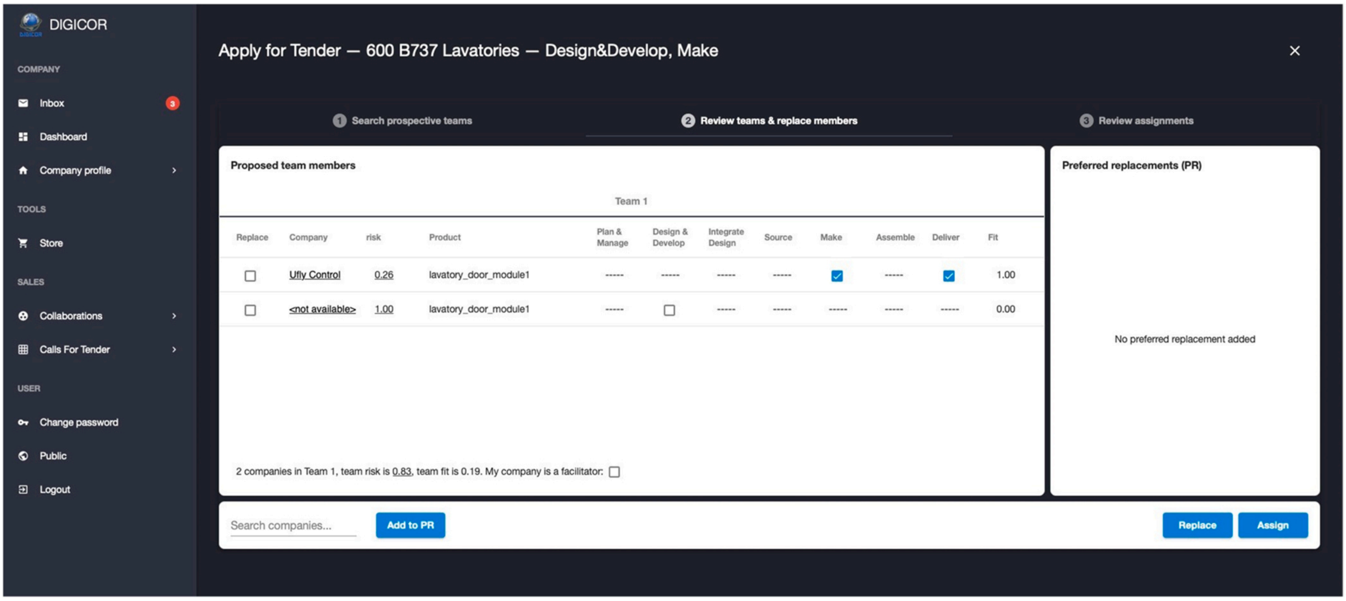
Fig. 13. TDMS UI: 1st screen 'Search prospective teams' with an element of the product structure highlighted.

to the respective companies and displayed on the third screen of the TDMS UI (Fig. 15-3). The user may delete undesired task assignments on this screen. As a result of this process of team formation, the user may end up with a team that is either incomplete or contains redundant tasks. Before passing the resulting team to the Collaboration Service, the user can examine the team completeness using the *Check* button. A message window will inform the user on specific gaps and redundancies in the team composition (Fig. 15-3). Pressing the *Proceed* button will start the collaboration.

As we developed the platform by instantiating the end-to-end solution through combining loosely coupled system services, the platform enables the 'unbundling' of architectural components, such as TDMS, and running them as standalone services. A live demonstration of the TDMS running as a standalone service can be accessed at http://130.88.97.225:4200 (username: TDMS@uniman.eu; password: uniman).

6.2. Use case: fulfil

The SCM Collaboration in the DIGICOR platform is described by use case (UC) Fulfil. UC Fulfil describes the serial production of a product/service by collaborating suppliers contracted by the OEM. It focuses on the creation of physical artifacts (the "actual product"). Thus, CPS (cyber-physical systems) aspects come into play, and



Apply for Tender — 600 B737 Lavatories — Design&Develop, Make

Proposed team members

Team 1

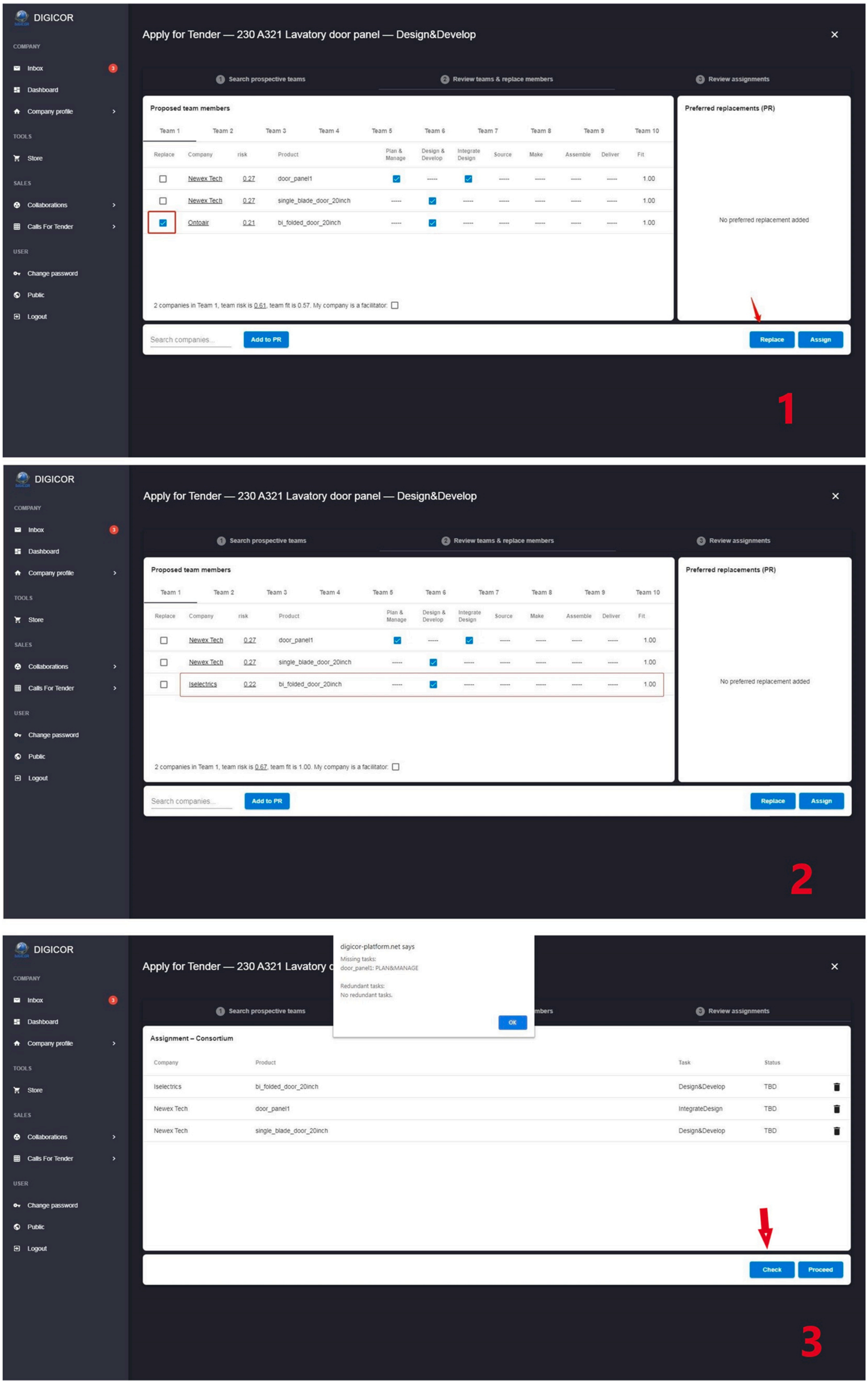
Replace	Company	risk	Product	Plan & Manage	Design & Develop	Integrate Design	Source	Make	Assemble	Deliver	Fit
☐	Ufly Control	0.26	lavatory_door_module1	-----	-----	-----	-----	☑	-----	☑	1.00
☐	<not available>	1.00	lavatory_door_module1	-----	☐	-----	-----	-----	-----	-----	0.00

2 companies in Team 1, team risk is 0.83, team fit is 0.19. My company is a facilitator: ☐

Preferred replacements (PR)

No preferred replacement added

Fig. 14. TDMS UI: second screen 'Review teams & replace members' with the search results.



Apply for Tender — 230 A321 Lavatory door panel — Design&Develop

Proposed team members

Replace	Company	risk	Product	Plan & Manage	Design & Develop	Integrate Design	Source	Make	Assemble	Deliver	Fit
☐	Newex Tech	0.27	door_panel1	☑	-----	☑	-----	-----	-----	-----	1.00
☐	Newex Tech	0.27	single_blade_door_20inch	-----	☑	-----	-----	-----	-----	-----	1.00
☑	Ontoair	0.21	bi_folded_door_20inch	-----	☑	-----	-----	-----	-----	-----	1.00

2 companies in Team 1, team risk is 0.61, team fit is 0.57. My company is a facilitator: ☐

Apply for Tender — 230 A321 Lavatory door panel — Design&Develop

Proposed team members

Replace	Company	risk	Product	Plan & Manage	Design & Develop	Integrate Design	Source	Make	Assemble	Deliver	Fit
☐	Newex Tech	0.27	door_panel1	☑	-----	☑	-----	-----	-----	-----	1.00
☐	Newex Tech	0.27	single_blade_door_20inch	-----	☑	-----	-----	-----	-----	-----	1.00
☐	Iselectrics	0.22	bi_folded_door_20inch	-----	☑	-----	-----	-----	-----	-----	1.00

2 companies in Team 1, team risk is 0.67, team fit is 1.00. My company is a facilitator: ☐

Apply for Tender — 230 A321 Lavatory d

digicor-platform.net says
Missing tasks:
door_panel1: PLAN&MANAGE

Redundant tasks:
No redundant tasks.

Assignment – Consortium

Company	Product	Task	Status
Iselectrics	bi_folded_door_20inch	Design&Develop	TBD
Newex Tech	door_panel1	IntegrateDesign	TBD
Newex Tech	single_blade_door_20inch	Design&Develop	TBD

Fig. 15. TDMS UI: (1) Selecting a team member for replacement; (2) Result of replacing the team member; (3) 3rd screen 'Review assignments' with *Check* and *Proceed* buttons and outcomes of the completeness check.

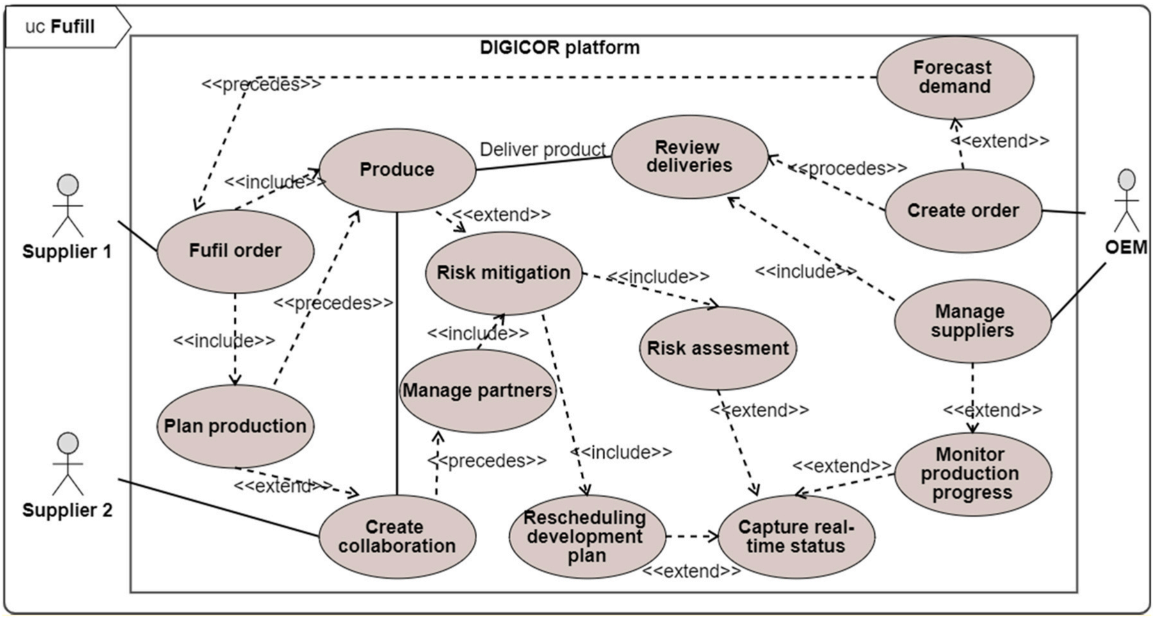


Fig. 16. Fulfil use case diagram.

interfacing with the shop floor (factory systems, sensors) takes place. The details of the cooperation then strongly depend on the Factory connectivity infrastructure. Fig. 16 shows the use case diagram of fulfil. All collaboration activities are supported by the Collaboration Node. The collaboration process in the platform is controlled in the following way: using the Collaboration Node as a mediator providing only the routing of event messages among tools/services installed in the individual Company Nodes. For brevity and focus, the screenshots of the collaboration process in the DIGICOR platform and other pre-collaboration use cases are presented in (DIGICOR, 2019).

7. Conclusions, managerial implications, and future work

This paper presents the architecture design and implementation of the DIGICOR collaborative I4.0 platform. We also include a survey comparing and contrasting DIGICOR with other I4.0 platforms. DIGICOR supports the entire lifecycle of I4.0 collaborations, from creation of viable teams to deployment and operation of demand-driven collaborations (Kazantsev et al., 2022). The DIGICOR architecture and platform embodies a vision of Industry 4.0 that enables SMEs to pool production capacities and capabilities towards forming a virtual enterprise capable of bidding for large tenders typically fulfilled by large companies operating as Tier-1 suppliers. DIGICOR also uses semantic technologies as an underpinning foundation for integrating a variety of services and providing: (i) a marketplace for tools supporting planning and control of collaborative production, logistics, and risk management, open to third parties; (ii) seamless connectivity to factory floor systems, smart objects and real-time data sources; (iii) an extensible architectural design including an API for companies to create and operate collaborative networks across value chains enforcing governance rules for collaborative production, knowledge protection and security. A prototype implementation of DIGICOR has been used to validate and test the proposed architecture. The application prototype implemented illustrates how the architecture reduces collaboration barriers and supports virtual team formations between OEMs and SMEs from the automotive and aerospace industries.

Digital platforms have attracted considerable attention and enjoyed strong adoption in diverse sectors over the recent years (Thomas et al., 2014; Taylor, 2018; Constantinides et al., 2018; Ha et al., 2021). In broad terms, digital platforms represent “a set of digital resources that enable value-creating interactions between external producers and consumers” (Constantinides et al., 2018). As such, digital platforms share several common characteristics. First, they typically own neither the goods and services involved in the exchange nor the physical assets involved in production of these (Thomas et al., 2014; Constantinides et al., 2018). Instead, platforms serve as a hub facilitating exchange between the parties by providing them with access to broader markets, reducing search and transaction costs, and offering a better matching of demand with supply and a better resource allocation (Thomas et al., 2014; Constantinides et al., 2018; Benjaafar et al., 2019). Second, platforms tend to maintain an architectural approach driven by the principles of openness and modularity, which broadens the platform’s scope in terms of products and industries, and invites third parties to join the platform, thus increasing its value offerings (Thomas et al., 2014; Constantinides et al., 2018). Third, platforms are facing the need to adopt governance mechanisms that would allow them to strike a balance between openness and control, to cope with behavioral complexity and remain stable but evolvable (Constantinides et al., 2018). And fourth, platform owners shall strike a balance between securing their own interests and those of platform members because platform owners benefit from the volume of exchange occurring on the platform (Thomas et al., 2014; Taylor, 2018; Constantinides et al., 2018).

These considerations let us derive managerial implications for collaborative I4.0 platforms, such as the DIGICOR, aiming at enabling SMEs to dynamically form and operate supply-chain collaborations. First, to serve as a hub effectively facilitating exchange between producers and their customers, such a platform shall provide an easy-to-access digital infrastructure (Constantinides et al., 2018) to let companies of any size and scope join the platform. Given the multi-level product structures and the resulting multi-tier supply chain structures, the platform shall allow matching of demand with supply at multiple levels of product structures and permit flexible representation of such product structures on the platform as well as various relationships between them (Cisneros-Cabrera et al., 2021). In this regard, the platform shall ideally remain product-agnostic and permit cross-industry participation (Constantinides et al., 2018).

Use of semantically driven approaches, such as product ontologies, may pave the way to such flexibility.

Second, to maintain openness and modularity, such a platform shall implement an architecture that would permit a simple inclusion of new services. A possible approach towards this is to let the platform offer a set of core services and accommodate optional ones, with loose coupling between them (Constantinides et al., 2018). Such coupling could be achieved by means of event-driven communication, as implemented in the DIGICOR. In this regard, the DIGICOR's Tool Store is conceived to house optional services that platform members can choose to instantiate in their infrastructure, which paves the way to attracting third-party providers of value-adding services on the platform and potentially creates network effects (Constantinides et al., 2018). Third, implementing digital governance becomes inevitable for such a platform to secure members' trust and deal with behavioral complexity, especially given that multi-firm supply-chain collaborations extend over time and involve multi-stage, distributed decision making. A proper coordination between multiple firms within a collaboration paves the way for the collaboration to effectively compete against large incumbent firms (Constantinides et al., 2018).

Fourth, monetization of the platform needs to be implemented in a way that would secure a critical mass of suppliers and buyers as well as third-party service providers, to ensure platform growth. At the same time, it needs to secure financial sustainability of the platform, as the platform growth requires to scale up and maintain its infrastructure (Constantinides et al., 2018). Apart from that, platform operation needs to contribute to the attainment of the platform owner's objectives — which, depending on the owner, can involve maximization of profit or social welfare (Constantinides et al., 2018; Benjaafar et al., 2019). A variety of approaches exist in this regard, such as charging transaction fees, membership fees, and third-party service fees, as well as subsidizing one side of the market at the expense of others (Thomas et al., 2014; Constantinides et al., 2018). Given the multi-level structure of supply-chain collaborations and the resulting tiered structure of supply and demand markets, additional research is needed to understand the dynamics of network effects and membership on such a platform as DIGICOR in relation to the monetization strategy.

The DIGICOR platform has been recently integrated into the European Connected Factory Platform for Agile Manufacturing (EFPF)[7] — an ongoing project funded by the European Commission's Horizon 2020 programme on Factories of the Future. EFPF uses DIGICOR's matchmaking and distributed production planning services to enable users to develop custom solutions to increase interoperability and efficiency across the supply chains. DIGICOR services such as TDMS (Cisneros-Cabrera et al., 2021) are also being investigated in the context of supporting smart contracts and automatic B2B advice acceptance for forming supply chain collaborations, enabling hyperconnected autonomous supply chains where parts of the supply chain ecosystem constantly learn and undergo self-adaptations to increase supply chain efficiency. Future research will also study the computational complexity of tender decomposition and matchmaking covering cross-industry supply chains.

Appendix

See here: Table A1.

CRediT authorship contribution statement

Dr. Zixu Liu: Conceptualization, Software Design & Programming, Software Architecture Design & Development, Use Case Planning, Use Case Validation, Writing Sections of Original Draft, Writing – Review & Editing, Paper Structure Design. **Dr. Pedro Sampaio:** Conceptualization, Methodology, Software Architecture Design, Validation Planning, Writing – Review & Editing, Resource Management (HR Allocation), Paper Structure Design, Project Management, Project Administration, Project Co-Direction.. **Dr. Grigory Pishchulov:** Conceptualization, Methodology, Software Architecture Design & Development, Software Programming, Use Case Planning, Use Case Validation, Writing a Section of Original Draft, Writing – Review & Editing, Resource Management (Data, Software, People), Project Management, Project Administration. **Prof. Nikolay Mehandjiev:** Conceptualization, Methodology, Software Architecture Design, Validation Planning, Writing – review & editing, Resource Management (HR Allocation and Finances), Project Management, Project Administration, Lead Project Direction, Funding Acquisition. **Dr. Sonia Cisneros-Cabrera**: Methodology, Software Architecture Design & Development, Writing a Section of Original Draft, Resource Management (Data, Software, People), Project Administration, Project Area Management. **Mr. Arnd Schirrmann**: Conceptualization, Methodology, Software Architecture Design, Validation Planning, Resource Management (HR Allocation and Finances), Project Management, Project Administration, Lead Project Direction, Funding Acquisition. **Dr. Filip Jiru:** Conceptualization, Methodology, Software Architecture Design, Validation Planning, Project Management, Project Administration. **Dr. Nisrine Bnouhanna:** Conceptualization, Methodology, Software Architecture Design & Development, Validation Planning.

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.

Acknowledgements

This work has received funding from the European Commission under the European Union's Horizon 2020 research and innovation programme (grant agreement n° 723336). Financial support has been provided from the National Council of Science and Technology (abbreviated CONACyT) to Sonia Cisneros-Cabrera (agreement n° 461338).

---

[7] https://www.efpf.org/

Table A1
The details of the participants of the activities listed in Table 3.

Description	Date & Number of participants	Field	Expertise	Role/Position
Aerospace Cluster Workshop	October 2017, 5 people	Aerospace	There is no quantitative information available; however, the participants were people invited because of their involvement in the aerospace industry, and particularly in the collaborative team formation processes within their companies.	
Aerospace OEM Workshop	October 2017, 4 respondents	Aerospace		
Connected Smart Factories Workshop	September 2018, 14 people	Academic – 36%Industry – 57%Both – 7%	Experience in forming collaborative teams – 100% ● > 10 years of experience– 29% ● 3-10 years of experience – 42% ● < 3 years of experience– 29%	Operations/Supply chain professional – 36%IT developer/systems engineer/architect – 29%Academic & Others – 21% eachExecutive/manager – 14%Business/IT consultant – 7%(some participants indicated more than 1 role)
Hamburg Expo Air Show More details and insights can be found in (Cisneros-Cabrera et al., 2020).	April 2019, 20 people	Aerospace - 75%One respondent each in: Industrial, Research & Consulting, and Logistics.	Experience in forming collaborative teams – 100% ● > 10 years of experience in forming collaborative teams – 35% ● Experience in using computerised systems for forming collaborative teams – 65% ● > 10 years of experience in using computerised systems for forming collaborative teams – 20%	CEOs – 20%Logistics Professionals – 15%Managing Directors – 10%Sales Managers – 10%One each: Aviation Journalist, a Cabin Project Manager, a Chair, a Corporate Manager, a Head of Design, an Operations Director, a Product Manager, a Project Manager, and a Research professional.
Paris Air Show	June 2019, 36 people	Aerospace and other manufacturing domains (e.g., metallurgy)	Experience in forming collaborative teams – 97% Experience in using computerised systems for forming collaborative teams – 80%	Sales – 22%Purchasing managers – 8%Aircraft systems engineers – 8%CEO – 8%Aircraft interiors engineers - 5%Vice president – 3%Managing director – 3%The rest is diversified in participants from research, cluster managers, business development, composite engineers, and business managers.
Aerospace Cluster Community event	June 2019, 5 people	Aerospace	Experience in forming collaborative teams – 60% ● > 10 years of experience in forming collaborative teams – 20%	Business managers – 80%One Vice President of an aerospace company.
Automotive & Robotics Cluster Community event	October 2019, 18 people	Automotive & Robotics	Experience in forming collaborative teams – 94% ● > 10 years of experience in forming collaborative teams – 44%	"Director level" – 28%Project Managers – 28%CEO – 11%IT graduates – 11%Technical Director – 6%One person each in research, sales, systems engineer, control, and advisory roles.

References

Ahluwalia, M., CHEN, Z., Gangopadhyay, A., GUO, Z., 2007. Preserving Privacy in Supply Chain Management: A Challenge for Next Generation Data Mining Proc. Natl. Sci. Found. Symp. Gener. Data Min. Cyber-Enabled Discov. Innov. NGDM 2007, 1.

Alibaba.com: Manufacturers, Suppliers, Exporters & Importers from the world's largest online B2B marketplace, (n.d.). ⟨https://www.alibaba.com/⟩ (Accessed 13 November 2019).

Alic, A.S., Almeida, J., Aloisio, G., Andrade, N., Antunes, N., Ardagna, D., Badia, R.M., Basso, T., Blanquer, I., Braz, T., Brito, A., Elia, D., Fiore, S., Guedes, D., Lattuada, M., Lezzi, D., Maciel, M., Meira, W., Mestre, D., Moraes, R., Morais, F., Pires, C.E., Kozievitch, N.P., dos Santos, W., Silva, P., Vieira, M., 2019. BIGSEA: a big data analytics platform for public transportation information. Futur. Gener. Comput. Syst. 96, 243–269. https://doi.org/10.1016/j.future.2019.02.011

Almeida, R.B., Junes, V.R.C., da S. Machado, R., da Rosa, D.Y.L., Donato, L.M., Yamin, A.C., Pernas, A.M., 2019. A distributed event-driven architectural model based on situational awareness applied on internet of things. Inf. Softw. Technol. 111, 144–158. https://doi.org/10.1016/j.infsof.2019.04.001

Amazon Business, (n.d.). ⟨https://www.amazon.com/b2b/info/amazon-business%3Flayout%3Dlanding⟩ (Accessed 13 November 2019).

APICS, Design Chain Operations Reference Model, 2013.

ATA, ATA specification 100 specification for manufacturers technical data, 1999.

Benjaafar, S., Kong, G., Li, X., Courcoubetis, C., 2019. Peer-to-peer product sharing: Implications for ownership, usage, and social welfare in the sharing economy. Manag. Sci. 65 (2), 477–493.

Bitkom, VDMA, ZVEI, Implementation Strategy Industrie 4.0 Report on the results of the Industrie 4.0 Platform, 2015.

Bnouhanna, N., Neugschwandtner, G., 2019. Cross-factory information exchange for cloud-based monitoring of collaborative manufacturing networks 2019 24th. IEEE Int. Conf. Emerg. Technol. Fact. Autom. 1203, 1206. https://doi.org/10.1109/ETFA.2019.8869033

Büyüközkan, G., Göçer, F., 2018. Digital supply chain: literature review and a proposed framework for future research. Comput. Ind. 97, 157–177. https://doi.org/10.1016/j.compind.2018.02.010

Camarinha-Matos, L.M., Afsarmanesh, H., 1999. The virtual enterprise concept. In: Infrastructures Virtual Enterp. Springer, pp. 15–30. https://doi.org/10.1007/978-0-387-35577-1_1

Camarinha-Matos, L.M., Fornasiero, R., Afsarmanesh, H., 2017. Collaborative networks as a core enabler of industry 4.0. : IFIP Adv. Inf. Commun. Technol. 3–17. https://doi.org/10.1007/978-3-319-65151-4_1

Camarinha-Matos, L.M., Afsarmanesh, H., Galeano, N., Molina, A., 2009. Collaborative networked organizations - concepts and practice in manufacturing enterprises. Comput. Ind. Eng. 57 (1), 46–60. https://doi.org/10.1016/j.cie.2008.11.024

Chandra, C., Tumanyan, A., 2007. Organization and problem ontology for supply chain information support system. Data Knowl. Eng. 61, 263–280.

Chiarello, F., Trivelli, L., Bonaccorsi, A., Fantoni, G., 2018. Extracting and mapping industry 4.0 technologies using wikipedia. Comput. Ind. 100, 244–257. https://doi.org/10.1016/J.COMPIND.2018.04.006

Cisneros-Cabrera, S., Ramzan, A., Sampaio, P., Mehandjiev, N., 2017. Digital marketplaces for Industry 4.0: a survey and gap analysis. : IFIP Adv. Inf. Commun. Technol. 18–27. https://doi.org/10.1007/978-3-319-65151-4_2

Cisneros-Cabrera, S., Pishchulov, G., Sampaio, P., Mehandjiev, N., Liu, Z., Kununka, S., 2021. An approach and decision support tool for forming industry 4.0 supply chain collaborations. Comput. Ind. 125, 103391. https://doi.org/10.1016/j.compind.2020.103391

Cisneros-Cabrera, S., Felfernig, A., Mehandjiev, N., Sampaio, P, Kununka, S., A laddering approach to explore the motivations of taking computer advice for supply networks formation, in: Beitrag 24th Pacific Asia Conf. Inf. Syst. Inf. Syst. Futur., PACIS 2020, Dubai, 2020.

cloudBuy brings B2B buyers and sellers together to trade online, (n.d.). ⟨https://www.cloudbuy.com/⟩ (Accessed 13 November 2019).

Coito, T., Martins, M.S.E., Viegas, J.L., Firme, B., Figueiredo, J., Vieira, S.M., Sousa, J.M.C., 2020. A middleware platform for intelligent automation: an industrial prototype implementation. Comput. Ind. 123, 103329. https://doi.org/10.1016/J.COMPIND.2020.103329

Constantinides, P., Henfridsson, O., Parker, G.G., 2018. Introduction—platforms and infrastructures in the digital age. Inf. Syst. Res. 29 (2), 381–400. https://doi.org/10.1287/isre.2018.0794

Cotrino, A., Sebastián, M.A., González-Gaya, C., 2021. Industry 4.0 HUB: a collaborative knowledge transfer platform for small and medium-sized enterprises. Appl. Sci. 11. https://doi.org/10.3390/app11125548

Creswell, J.W., Creswell, J.D., 2017. Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. Sage publications.

Dalenogare, L.S., Benitez, G.B., Ayala, N.F., Frank, A.G., 2018. The expected contribution of Industry 4.0 technologies for industrial performance. Int. J. Prod. Econ. 204, 383–394. https://doi.org/10.1016/J.IJPE.2018.08.019

Dallasega, P., Rauch, E., Linder, C., 2018. Industry 4.0 as an enabler of proximity for construction supply chains: a systematic literature review. Comput. Ind. 99, 205–225. https://doi.org/10.1016/j.compind.2018.03.039

DIGICOR, Digicor Portal User Manual, 2019. ⟨https://6c97d07e-2d66–4f14–9c19–8c5872c4c3ba.filesusr.com/ugd/2512a7_1adcfe4f0c6148b9868f0649eccd9341.pdf⟩.

Digital Marketplace, (n.d.). ⟨https://www.digitalmarketplace.service.gov.uk/⟩ (Accessed 13 November 2019).

Dobrescu, R., Merezeanu, D., Mocanu, S., 2019. Process simulation platform for virtual manufacturing systems evaluation. Comput. Ind. 104, 131–140. https://doi.org/10.1016/J.COMPIND.2018.09.008

Dolenc, M., Katranuschkov, P., Gehre, A., Kurowski, K., et al., 2007. The InteliGrid platform for virtual organisations interoperability. J. Inf. Technol. Constr. 12, 459–477.

European Commission, Digital Automation, Res. Innov. Oppor. 2015.

Ferreira, F., Faria, J., Azevedo, A., Marques, A.L., 2016. Industry 4.0 as enabler for effective manufacturing virtual enterprises. IFIP Adv. Inf. Commun. Technol. 274–285. https://doi.org/10.1007/978-3-319-45390-3_24

Gangemi, A., Sagri, M.T., Tiscornia, D., 2005. A constructive framework for legal ontologies. Lect. Notes Comput. Sci. 97–124. https://doi.org/10.1007/978-3-540-32253-5_7. (Incl. Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinforma.).

Ghadge, A., Er Kara, M., Moradlou, H., Goswami, M., 2020. The impact of Industry 4.0 implementation on supply chains. J. Manuf. Technol. Manag 31, 669–686. https://doi.org/10.1108/JMTM-10-2019-0368

Gilchrist, A., Gilchrist, A., 2016. Introducing Industry 4.0. in: Ind. 4.0. pp. 195–215. https://doi.org/10.1007/978-1-4842-2047-4_13

Gunasekaran, A., Lai, K.-h., Cheng, T.C.E., 2008. Responsive supply chain: a competitive strategy in a networked economy. Omega 36, 549–564. https://doi.org/10.1016/j.omega.2006.12.002

Ha, A.Y., Luo, H., Shang, W., 2021. Supplier encroachment, information sharing, and channel structure in online retail platforms. Prod. Oper. Manag. https://doi.org/10.1111/poms.13607

Hannelius, T., Salmenperä, M., Kuikka, S., 2008. Roadmap to adopting OPC UA. IEEE Int. Conf. Ind. Inform. 756–761. https://doi.org/10.1109/INDIN.2008.4618203

Hauser, K., Sigurdsson, H.S., Chudoba, K.M., 2010. EDSOA: an event-driven service-oriented architecture model for enterprise applications. Int. J. Manag. Inf. Syst. 14.

Helo, P., Szekely, B., 2005. Logistics information systems: an analysis of software solutions for supply chain co-ordination. Ind. Manag. Data Syst. 105, 5–18. https://doi.org/10.1108/02635570510575153

Hevner, A., Chatterjee, S., 2010. (in). Des. Sci. Res. Inf. Syst. 9–22. https://doi.org/10.1007/978-1-4419-5653-8_2

Hevner, A.R., March, S.T., Park, J., Ram, S., 2004. Design science in information systems research. MIS Q. 28, 75–105. https://doi.org/10.2307/25148625

HewaNadungodage, C., Catlin, A.C., Bejarano, A., Clark, S., Wickramaarachchi, G., Fernando, S., Desigavinayagam, P., 2019. The DEEDS platform: Support for integrated data and computing across the research lifecycle. Futur. Gener. Comput. Syst. 111, 793–805.

Hofmann, E., Rüsch, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. Comput. Ind. 89, 23–34. https://doi.org/10.1016/j.compind.2017.04.002

Innerbichler, J., Gonul, S., Damjanovic-Behrendt, V., Mandler, B., Strohmeier, F., 2017. NIMBLE collaborative platform: Microservice architectural approach to federated IoT. 2017 Global Internet of Things Summit (GIoTS) 2017, 1–6. https://doi.org/10.1109/GIOTS.2017.8016216

Jirkovský, V., D 5.10: Semantic Data Models Implementation, DIGICOR project deliverable, 2019. ⟨https://6c97d07e-2d66–4f14–9c19–8c5872c4c3ba.filesusr.com/ugd/2512a7_a179fbe72cc240dca614e73207ab62ea.pdf⟩.

Juneau J. RESTful Web Services 2018. https://doi.org/10.1007/978–1-4842–3594-2_15.

Kagermann, H., 2015. Change through digitization—value creation in the age of industry 4.0. Manag. Perm. Chang 23–45. https://doi.org/10.1007/978-3-658-05014-6_2

Kazantsev, N., Pishchulov, G., Mehandjiev, N., Sampaio, P., 2018. Exploring barriers in current inter-enterprise collaborations: a survey and thematic analysis. Lect. Notes Bus. Inf. Process. 319–327. https://doi.org/10.1007/978-3-319-94214-8_23

Kazantsev, N., Pishchulov, G., Mehandjiev, N., Sampaio, P., Zolkiewski, J., 2022. Investigating barriers to demand-driven SME collaboration in low-volume high-variability manufacturing. Supply Chain Manag. Int. J. https://doi.org/10.1108/SCM-10-2021-0486

Kazantsev, N., Mehandjiev, N., Sampaio, P., Stalker, I.D., Ramzan, A., 2018. A Collaboration Design Method for Fostering Demand-driven Collaborations in Industry 4.0, ⟨https://www.researchgate.net/publication/325676140_A_Collaboration_Design_Method_for_Fostering_Demand-driven_Collaborations_in_Industry_40⟩.

Keshavarzian, A., Sharifian, S., Seyedin, S., 2019. Modified deep residual network architecture deployed on serverless framework of IoT platform based on human activity recognition application. Futur. Gener. Comput. Syst. 101, 14–28. https://doi.org/10.1016/j.future.2019.06.009

Koch, V., Kuge, S., Geissbauer, R., Schrauf, S., 2014. Industry 4.0 - Opportunities and challenges of the industrial internet. Strateg. Former. Booz Company PwC 5–50.

Kochovski, P., Gec, S., Stankovski, V., Bajec, M., Drobintsev, P.D., 2019. Trust management in a blockchain based fog computing platform with trustless smart oracles. Futur. Gener. Comput. Syst. 101, 747–759. https://doi.org/10.1016/j.future.2019.07.030

Koleva, N., 2018. Industry 4.0′s opportunities and challenges for production engineering and management. Innovations 6, 17–18.

Kratzwald, B., Feuerriegel, S., 2019. Putting question-answering systems into practice: transfer learning for efficient domain customization. ACM Trans. Manag. Inf. Syst. 9 (4), 1–20. https://doi.org/10.1145/3309706

Laliwala, Z., Chaudhary, S., Event-driven service-oriented architecture 5th Int. Conf. Serv. Syst. Serv. Manag. - Explor. Serv. Dyn. Sci. Innov. Technol. ICSSSM'08 2008 1 6 doi: 10.1109/ICSSSM.2008.4598452.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., Hoffmann, M., 2014. Industry 4.0. Bus. Inf. Syst. Eng. 6, 239–242.

Lee, C.S., Jiang, C.C., Hsieh, T.C., 2006. A genetic fuzzy agent using ontology model for meeting scheduling system. Inf. Sci. 176 (9), 1131–1155. https://doi.org/10.1016/j.ins.2005.07.012

Lennon Olsen, T., Tomlin, B., 2019. Industry 4.0: opportunities and challenges for operations management. Manuf. Serv. Oper. Manag. 22 (1), 113–122.

Li, Q., Tang, Q., Chan, I., Wei, H., Pu, Y., Jiang, H., Li, J., Zhou, J., 2018. Smart manufacturing standardization: architectures, reference models and standards framework. Comput. Ind. 101, 91–106. https://doi.org/10.1016/j.compind.2018.06.005

Liese, H., Rulhoff, S., Stjepandic, J., 2013. Enhancing product innovation by implementing intellectual property protection into the virtual product creation. In: Stjepandić, J., Rock, G., Bil, C. (Eds.), Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment. Springer, London, London, pp. 267–278.

Linthicum, D. , Chapter 1: Service Oriented Architecture (SOA), 〈Https://Msdn.Microsoft.Com/En-Us/Library/Bb833022.Aspx〉. (2016).

Liu, C., Jiang, P., 2016. A Cyber-physical System Architecture in Shop Floor for Intelligent Manufacturing. Procedia CIRP 56, 372–377. https://doi.org/10.1016/j.procir.2016.10.059

Liu, Q., Zhang, H., Leng, J., Chen, X., 2019. Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system. Int. J. Prod. Res. 57, 3903–3919. https://doi.org/10.1080/00207543.2018.1471243

Liu, Z., Han, J., Meng, F., Liao, H., 2021. A cloud-based and web-based group decision support system in multilingual environment with hesitant fuzzy linguistic preference relations. Int. J. Intell. Syst. https://doi.org/10.1002/int.22789

Longo, F., Nicoletti, L., Padovano, A., 2019. Emergency preparedness in industrial plants: a forward-looking solution based on industry 4.0 enabling technologies. Comput. Ind. 105, 99–122. https://doi.org/10.1016/j.compind.2018.12.003

Luzuriaga, J.E., Perez, M., Boronat, P., Cano, J.C., Calafate, C., Manzoni, P., 2015. A comparative evaluation of AMQP and MQTT protocols over unstable and mobile networks 2015 12th Annu. IEEE Consum. Commun. Netw. Conf. CCNC 2015 (931), 936. https://doi.org/10.1109/CCNC.2015.7158101

Lv, Z., Li, X., Wang, W., Zhang, B., Hu, J., Feng, S., 2018. Government affairs service platform for smart city. Futur. Gener. Comput. Syst. 81, 443–451. https://doi.org/10.1016/j.future.2017.08.047

Mesquita, L.F., Ragozzino, R., Reuer, J.J., 2017. Collaborative Strategy: Critical issues for Alliances and Networks. Edward Elgar Publishing,.

Mukherjee, A., Sundarraj, R.P., Dutta, K., 2017. Apriori rule-based in-app ad selection online algorithm for improving supply-side platform revenues. ACM Trans. Manag. Inf. Syst. 8 (2–3), 1–28. https://doi.org/10.1145/3086188

Oberle, D., Ankolekar, A., Hitzler, P., Cimiano, P., Sintek, M., Kiesel, M., Mougouie, B., Baumann, S., Vembu, S., Romanelli, M., Buitelaar, P., Engel, R., Sonntag, D., Reithinger, N., Loos, B., Zorn, H.P., Micelli, V., Porzel, R., Schmidt, C., Weiten, M., Burkhardt, F., Zhou, J., 2007. DOLCE ergo SUMO: On foundational and domain models in the SmartWeb Integrated Ontology (SWIntO). Web Semant. 5 (3), 156–174. https://doi.org/10.1016/j.websem.2007.06.002

Obitko, M., Jirkovský, V., 2015. Big data semantics in industry 4.0. Int. Conf. Ind. Appl. Holonic Multi-Agent Syst. 217, 229.

OPC foundation, OPC Unified Archietcture: Interoperability for Industrie 4.0 and the Internet of Things, 2020. 〈https://opcfoundation.org/wp-content/uploads/2017/11/OPC-UA-Interoperability-For-Industrie4-and-IoT-EN.pdf〉.

Pautasso, C., Zimmermann, O., Leymann, F., RESTful web services vs. "Big" web services: Making the right architectural decision Proc. 17th Int. Conf. World Wide Web 2008, WWW'08 2008 805 814 doi: 10.1145/1367497.1367606.

Peres, R.S., Dionisio Rocha, A., Leitao, P., Barata, J., 2018. IDARTS – Towards intelligent data analysis and real-time supervision for industry 4.0. Comput. Ind. 101, 138–146. https://doi.org/10.1016/j.compind.2018.07.004

Pishchulov, G., Quboa, Q., Mehandjiev, N., 2022. Forming on-demand supply chain collaborations with evaluation of fit and risk. Procedia Comput. Sci. 200C, 1481–1487.

Pishchulov, G., Jimenez-Arriaga, A., Cisneros-Cabrera, S., Quboa, Q., Liu, Z., Ramzan, A., Kazantsev, N., Sampaio, P., Mehandjiev, N., 2019. Form. Supply-Chain Collab. Using DIGICOR's Tender Decompos. Matchmaking Serv.: A White Pap. Using TDMS A Standalone Serv. 〈https://www.research.manchester.ac.uk/portal/en/publications/forming-supplychain-collaborations-using-digicors-tender-decomposition-and-matchmaking-service(35996a8f-5aa7-453f-b832-2a02a3634ced).html〉.

Preeth, E.N., Mulericka, J.P., Paul, l B., Sastri, Y., 2015. Conf. Control. Commun. Comput. India, ICCC 2015, 2016. https://doi.org/10.1109/ICCC.2015.7432984

Pulparambil, S., Baghdadi, Y., Salinesi, C., 2021. A methodical framework for service oriented architecture adoption: guidelines, building blocks, and method fragments. Inf. Softw. Technol. 132, 106487. https://doi.org/10.1016/j.infsof.2020.106487

Purao, S., Bolloju, N., Tan, C.H., 2018. A modeling language for conceptual design of systems integration solutions. ACM Trans. Manag. Inf. Syst. 9 (2), 1–25. https://doi.org/10.1145/3185046

Ramzan, A., Cisneros-Cabrera, S., Sampaio, P., Mehandjiev, N., 2017. Dynamic Modelling of Production Supply Chains of Small and Medium Enterprises with Large Original Equipment Manufacturers in DIGICOR, In American Conference on Information Systems 2017: International Workshop on Smart Manufacturing: Business Meeting on Big Data Application in Manufacturing.

Ribu, K., 2001. Estimating object-oriented software projects with use cases. University of Oslo, Dept.

Romero, D., Vernadat, F., 2016. Enterprise information systems state of the art: Past, present and future trends. Comput. Ind. 79, 3–13. https://doi.org/10.1016/J.COMPIND.2016.03.001

Russo, D., Ciancarini, P., Falasconi, T., Tomasi, M., 2018. A meta-model for information systems quality: a mixed study of the financial sector. ACM Trans. Manag. Inf. Syst. 9 (3), 1–38. https://doi.org/10.1145/3230713

Schadel, J., Lockström, M., Moser, R., Harrison, N., 2016. Readiness for supply chain collaboration and supplier integration—findings from the Chinese automotive industry. In: Panwar, K.S., Roger, H., Potter, A., Naim, N. (Eds.), evelopments in Logistics and Supply Chain Management. Dev. Logist. Supply Chain Manag.pp. 125–137. https://doi.org/10.1057/9781137541253_12

Schipor, O.A., Vatavu, R.D., Vanderdonckt, J., 2019. Euphoria: a scalable, event-driven architecture for designing interactions across heterogeneous devices in smart environments. Inf. Softw. Technol. 109, 43–59. https://doi.org/10.1016/j.infsof.2019.01.006

Smit, J., Kreutzer, S., Moeller, C., Carlberg, M., 2016. Industry 4.0: study for the ITRE Committee, Policy Dep. A Econ. Sci. Policy, Eur. Parlam. EU.

Soille, P., Burger, A., De Marchi, D., Kempeneers, P., Rodriguez, D., Syrris, V., Vasilev, V., 2018. A versatile data-intensive computing platform for information retrieval from big geospatial data. Futur. Gener. Comput. Syst. 81, 30–40. https://doi.org/10.1016/j.future.2017.11.007

Sun, C., Ji, Y., Kolfal, B., Patterson, R., 2017. Business-to-consumer platform strategy: how vendor certification changes platform and seller incentives. ACM Trans. Manag. Inf. Syst. 8 (2–3), 1–42. https://doi.org/10.1145/3057273

Taylor, T.A., 2018. On-demand service platforms. Manuf. Serv. Oper. Manag. 20 (4), 704–720.

Terroso-Saenz, F., González-Vidal, A., Ramallo-González, A.P., Skarmeta, A.F., 2019. An open IoT platform for the management and analysis of energy data. Futur. Gener. Comput. Syst. 92, 1066–1079. https://doi.org/10.1016/j.future.2017.08.046

Thomas, L.D.W., Autio, E., Gann, D.M., 2014. Architectural leverage: putting platforms in context. Acad. Manag. Perspect. 28 (2), 198–219.

ThomasNet® - Product Sourcing and Supplier Discovery Platform - Find North American Manufacturers, Suppliers and Industrial Companies, (n.d.). 〈https://www.thomasnet.com/〉 (Accessed 13 November 2019).

Trappey, A.J.C., Hsiao, D.W., 2008. Applying collaborative design and modularized assembly for automotive ODM supply chain integration. Comput. Ind. 59, 277–287. https://doi.org/10.1016/j.compind.2007.07.001

Vaisband, B., Friedman, E.G., 2018. Heterogeneous 3-D ICs as a platform for hybrid energy harvesting in IoT systems. Futur. Gener. Comput. Syst. 87, 152–158. https://doi.org/10.1016/j.future.2018.04.092

Verba, N., Chao, K.M., Lewandowski, J., Shah, N., James, A., Tian, F., 2019. Modeling industry 4.0 based fog computing environments for application analysis and deployment. Futur. Gener. Comput. Syst. 91, 48–60. https://doi.org/10.1016/J.FUTURE.2018.08.043

vom Brocke, J., Maedche, A., 2019. The DSR grid: six core dimensions for effectively planning and communicating design science research projects. Electron. Mark. 29, 379–385.

Vom Brocke, J., Havner, A., Maedche, A., 2020. Design Science Research: Cases. Springer.

Vresk, T., Čavrak, I., 2016. Architecture of an interoperable IoT platform based on microservices 2016 39th Int. Conv. Inf. Commun. Technol. Electron. Microelectron. 1196, 1201.

Wang, B., Luo, W., Zhang, A., Tian, Z., Li, Z., 2020. Blockchain-enabled circular supply chain management: a system architecture for fast fashion. Comput. Ind. 123, 103324. https://doi.org/10.1016/J.COMPIND.2020.103324

Wang, S., Zhong, Y., Wang, E., 2019. An integrated GIS platform architecture for spatiotemporal big data. Futur. Gener. Comput. Syst. 94, 160–172. https://doi.org/10.1016/j.future.2018.10.034

Wang, Y., Han, J.H., Beynon-Davies, P., 2019. Understanding blockchain technology for future supply chains: a systematic literature review and research agenda. Supply Chain Manag. Int. J. 24, 62–84. https://doi.org/10.1108/SCM-03-2018-0148

Wang, Y., Ajoku, P.N., Brustoloni, J.C., Nnaji, B.O., 2005. Intellectual property protection in collaborative design through lean information modeling and sharing. J. Comput. Inf. Sci. Eng. 6, 149–159. https://doi.org/10.1115/1.2190235

Wieringa, R.J., 2014. Design science methodology: For information systems and software engineering. Springer.

Xu, L.D., Xu, E.L., Li, L., 2018X. Industry 4.0: state of the art and future trends. Int. J. Prod. Res. 56, 2941–2962. https://doi.org/10.1080/00207543.2018.1444806

Ye, Y., Yang, D., Jiang, Z., Tong, L., 2008. Ontology-based semantic models for supply chain management. Int. J. Adv. Manuf. Technol. 37, 1250–1260.

Zdravković, M., Panetto, H., Trajanović, M., Aubry, A., 2011. An approach for formalising the supply chain operations. Enterp. Inf. Syst. 5, 401–421.

Zeng, P., Wang, Z., Jia, Z., Kong, L., Li, D., Jin, X., 2019. Time-slotted software-defined industrial ethernet for real-time quality of service in industry 4.0. Futur. Gener. Comput. Syst. 99, 1–10. https://doi.org/10.1016/j.future.2019.04.009

Zhang, Y., Duan, L., Chen, J.L., 2014. Event-driven SOA for IoT services. Proc. - 2014 IEEE Int. Conf. Serv. Comput. SCC 2014, 629–636. https://doi.org/10.1109/SCC.2014.88

Zhang, Y., Zhang, G., Wang, J., Sun, S., Si, S., Yang, T., 2015. Real-time information capturing and integration framework of the internet of manufacturing things. Int. J. Comput. Integr. Manuf. 28 (8), 811–822. https://doi.org/10.1080/0951192X.2014.900874

Zheng, P., Wang, H., Sang, Z., Zhong, R.Y., Liu, Y., Liu, C., Mubarok, K., Yu, S., Xu, X., 2018. Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. Front. Mech. Eng. 13 (2), 137–150. https://doi.org/10.1007/s11465-018-0499-5

Zhou, K., Liu, T., Zhou, L., 2015. Industry 4.0: Towards future industrial opportunities and challenges 2015 12th. Int. Conf. Fuzzy Syst. Knowl. Discov. FSKD 2016, 2147–2152. https://doi.org/10.1109/FSKD.2015.7382284

Zo, H., Nazareth, D.L., Jain, H.K., 2019. Service-oriented application composition with evolutionary heuristics and multiple criteria. ACM Trans. Manag. Inf. Syst. 10 (3), 1–28.