Technological Forecasting & Social Change 197 (2023) 122917

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

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

From supply chains towards manufacturing ecosystems: A system dynamics model

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ARTICLE INFO

Keywords:
Demand-driven collaboration
SME
System dynamics
Manufacturing ecosystem
Aerospace
Industry 4.0

ABSTRACT

Rapid market changes call for demand-driven collaborations in manufacturing, which trigger supply chain evolution to more distributed supply structures. This paper explores the system dynamics of the largest European aerospace manufacturer's supply chain. We conceptualise a manufacturing ecosystem by observing the impacts of supplier development, digital platforms, smart contracting, and Industry 4.0 on demand-driven collaborations in time. We contribute to the literature on ecosystem strategy, particularly for regulated industries, by disclosing the role of demand-driven collaborations in supporting the ecosystems' growth. We provide manufacturing firms with an open-access tool to exemplify their ecosystem development and produce initial training datasets for AI/ML algorithms, supporting further analytics.

1. Introduction

During the last years of supply chain optimisation, Airbus has reduced direct supply relationships with >6000 multi-tier suppliers in favour of larger suppliers (Rossen et al., 2015). While these changes have increased cost efficiency in periods of stable demand, they have exhibited sourcing limitations during demand fluctuations (SCE, 2017; Schirrmann and Drat, 2018). Specifically, many small innovative firms have lost access to manufacturing orders, and when a larger demand occurs, they can not quickly pool their production capacities (Kazantsev et al., 2022). The present study explores how Original Equipment Manufacturers (OEMs), like Airbus, may support demand-driven collaboration across their supply chain and create more resilient supply structures – manufacturing ecosystems.

An ecosystem perspective is considered an attempt to build 'an economic community of interacting companies' (Jacobides et al., 2018, p. 2257) to exchange knowledge and research and to develop new products and services (Cusumano and Gawer, 2002; Gawer and Cusumano, 2014; Tiwana, 2015). Several authors have predicted the transformation of supply chains into manufacturing ecosystems characterised by collaborative arrangements and interdependence among actors from different industries (Benitez et al., 2020; Schmidt et al., 2020; Schmidt et al., 2022). For example, digitalisation policies, such as Industry 4.0, envisioned manufacturing ecosystems in early 2010 as 'integrated production processes along the entire value chain' (Smit et al., 2016). However, due to multiple barriers, such integration did not happen. The existing studies warn about the lack of market transparency, limited order access, low trust, high costs of contracting and coordination (Kazantsev et al., 2022), high uncertainty levels (Hannah and Eisenhardt, 2018; Moeen et al., 2020; Santos and Eisenhardt, 2009), the lack of clear guidance on collaborating (Frank et al., 2019; Raj et al., 2020) and the lack of knowledge sharing (Konsti-Laakso et al., 2012; Zeng et al., 2010). Literature on Industry 4.0 and ecosystems avoid discussion of the means to facilitate barriers to demand-driven collaborations (Ivanov et al., 2019; Ivanov et al., 2020; Olsen and Tomlin, 2020; Tang and Veelenturf, 2019), hence the ways how demand-driven collaboration may drive manufacturing ecosystems are underexplored (Ferrell et al., 2020). The research question (RQ) that guides this paper is as follows:

RQ: How can demand-driven collaboration convert supply chains into a manufacturing ecosystem?

In response, we conduct a case study of the largest European

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https://doi.org/10.1016/j.techfore.2023.122917
Received 6 September 2022; Received in revised form 1 October 2023; Accepted 2 October 2023
Available online 14 October 2023

aerospace manufacturer and use system dynamics to investigate outcomes at the ecosystem level. We picked a cluster of aerospace suppliers with specific disadvantages compared to large firms in digitisation, leading to lower collaboration efficiency (Horváth and Szabó, 2019). This cluster of companies was severely affected by cancellations of orders during the COVID-19 demand shock and considered novel ways to support demand-driven collaboration between their members. After simulating the application of supplier development, digital platforms, smart contracting, and Industry 4.0 as collaboration enablers (Kazantsev et al., 2022), we explore the system dynamics of the increased number of (i) tenders submitted, (ii) orders awarded to SMEs, and (iii) orders fulfilled in collaboration with SMEs. Notably, the number of orders fulfilled by SMEs overcomes the number of orders fulfilled by Tier-1 suppliers in the fourth year of supporting demand-driven collaboration.

To explain the answer to RQ, first, we demonstrate that investing in supplier development programs and digital B2B platforms is essential for increasing market transparency for smaller firms. Second, we show that digitalisation of contracting procedures (smart contracts) enables firms to reduce market uncertainty. Third, we explore Industry 4.0 tools for data sharing that enable better coordination on the market, helping teams fulfil multiple orders simultaneously.[2] Finally, we position collaboration experience of SMEs as the main driver for the manufacturing ecosystem growth, as it leads to more opportunities for novice firms to engage into demand-driven collaborations. Through these aims, we contribute to the literature on supply chain collaboration (MacCarthy et al., 2016) and ecosystem strategy (Cusumano and Gawer, 2002; Gawer and Cusumano, 2014; Tiwana, 2015). Particularly for nascent ecosystems (Hannah and Eisenhardt, 2018; McDonald and Eisenhardt, 2020) supported by multitier supply chains, the present paper suggests the enablers of demand-driven collaborations as a way to expedite ecosystem growth.

Section 2 explores the theory of ecosystems and technologies to enable their growth in manufacturing settings. Section 3 describes the methodology behind the system dynamics modelling of an aerospace manufacturing ecosystem. In Section 4, we list the findings from the simulation based on the data from several R&D projects. Section 5 discusses these findings concerning current literature and addresses theoretical, methodological, and managerial contributions. Finally, we conclude our findings, list limitations and future research opportunities.

2. Theoretical background

2.1. Industry 4.0

Several authors have introduced the concept of manufacturing ecosystems, referencing Industry 4.0 to explain complex digital interactions across multiple stakeholders (Benitez et al., 2020; Papert and Pflaum, 2017; Schmidt et al., 2020; Schmidt et al., 2022). Industry 4.0 is often associated with the next industrial revolution, enabled by the Internet of Things (IoT) and Cyber-Physical Systems (CPS). These technologies enable data collection, transmission, and analysis across an entire supply chain of a focal enterprise. This relates to the original concept of Industry 4.0, horizontal and vertical integration and across the entire product lifecycle (Kagermann et al., 2013; Lasi et al., 2014). Other technologies, such as advanced manufacturing technologies or human-machine interfaces, support merging real and virtual worlds across machines, humans, production facilities, and products (Kagermann et al., 2013). In particular, Industry 4.0 drives supply chain design towards ecosystem-based manufacturing (Benitez et al., 2020; Papert and Pflaum, 2017; Schmidt et al., 2020). Likewise, incorporating small- and medium-sized enterprises into the concept of Industry 4.0 is vital for its success but considerably challenging (Müller et al., 2018), as discussed in section 2.2 below.

2.2. Small- and medium-sized enterprises

Small- and medium-sized enterprises (SMEs) represent most companies worldwide, accounting for 70 % of jobs and generating up to 60 % of value added (OECD, 2017). SMEs' production volumes are precise and unstandardised, so even basic systems that allow sharing capacities or loads, such as ERP systems, are absent (Müller et al., 2018). Therefore, it is challenging for SMEs to integrate vertically, horizontally, and in end-to-end directions, as envisioned in Industry 4.0 (Kagermann et al., 2013). Moreover, their marketplaces are controlled by larger manufacturers, who select their sub-contractors (Fawcett et al., 2008; Schwab, 2017). Faustino et al. (2019) have noted that cluster governance, geographic proximity, and trust are the primary enablers of SME collaboration. Therefore, regional clusters help to introduce SMEs and facilitate the creation of supplier teams in response to business opportunities (Connell et al., 2014; Niu, 2010) and even collaborative business models (Dalmarco et al., 2019; Kazantsev and Martens, 2021; Müller and Buliga, 2019). As the participation of SMEs in manufacturing ecosystems is constrained (Frank et al., 2019; Kazantsev et al., 2018; Luthra and Mangla, 2018), enablers of demand-driven collaboration could allow SMEs to overcome some barriers. Several enablers conceptualised in this paper - Industry 4.0 technologies, digital platforms, smart contracts, and supplier development programs - are described in the following section.

2.3. Enablers of demand-driven collaboration

2.3.1. Digital technologies in Industry 4.0

Integrating supply chains based on digital technologies encompassed by Industry 4.0 involves integrating supply chain and manufacturing processes across the entire supply chain (Kagermann et al., 2013; Lasi et al., 2014). With the help of digital technologies, traditional vertical buyer-supplier supply chains can evolve into distributed supply structures (Benitez et al., 2020; Schmidt et al., 2020). However, such a transformation requires efforts in standardisation, cross-company data exchange, reduced uncertainty, and willingness to collaborate, all while managing competing interests among supply chain partners (Müller et al., 2020). Currently, SMEs lack technological infrastructure (Michaelides et al., 2013) and face multiple barriers to information exchange (Klein et al., 2018). However, when established, the increased level of transparency, traceability, and virtual integration of supply chains, in turn, is expected to lead to extended collaboration and awareness of the entire supply chain or even the ecosystem a single firm contributes to. This, in turn, can lead to multi-tier supply chain data exchange and collaboration, transforming supply chains into ecosystems (Benitez et al., 2020; Papert and Pflaum, 2017; Schmidt et al., 2020).

2.3.2. Digital platforms

Digital platform firms - partially subsumed under Industry 4.0 (Schmidt et al., 2022) - use digital technologies to 'facilitate connections across multiple sides, subject to cross-side network effects' (Gawer, 2021). Digital platforms are growing in popularity in manufacturing (MacCarthy et al., 2016), particularly in the European Union—notable examples include the EU-funded projects Digital Agile Collaboration Across Supply Chains (DIGICOR) or the European Factory Platform (EFPF). Such digital platforms enable matchmaking between suppliers, empowering smaller suppliers to collaborate on-demand (Thomas et al., 2014) and allowing for more resilient supply chains (Lotfi and Larmour, 2021; Scholten and Schilder, 2015). In addition, platforms increase the transparency of marketplaces, enable access to more capacities (Faustino et al., 2019), and facilitate product innovation (Adner and Kapoor, 2010; Payne and Frow, 2016; Thomas et al., 2014). For SMEs, the emergence of platforms triggers new technology adoption,

[2] We consider all the mechanisms supporting data sharing and interoperability, e.g., ontological engineering, as a part of the Industry 4.0 (Kazantsev et al., 2023)

Type of ecosystem (Jacobides et al., 2018)

Strategies for nascent ecosystems (Hannah & Eisenhardt, 2018)	*Producer-Based ecosystem*	*Platform-Based ecosystem*	*Multisided platform ecosystem*
System strategy	**OEM** provides a legal framework for work allocation (tendering) along their supply chain.	**OEM** introduces a digital B2B platform to facilitate demand-driven collaborations along their supply chain.	**OEM** opens an ecosystem for more actors (e.g., SMEs from other industries, data science firms, and start-ups).
Component strategy	**SMEs** are members of supply chain and provide semi-parts to multiple tiers.	**SMEs** try to collaborate with other SMEs in the supply chain to win more (and larger) orders.	**SMEs** collaborate across supply chains to submit collaborative tenders and fulfil orders.
Bottleneck strategy	**Tier-1** suppliers fulfil most profitable orders, with no (or limited) competition with other firms or demand-driven SME collaborations.		**Demand-driven SMEs collaborations** can compete with Tier 1 for most profitable orders

Fig. 1. Positioning within different types of ecosystems (Jacobides et al., 2018) and strategies for nascent ecosystems in manufacturing (Hannah and Eisenhardt, 2018).

organisational culture, and changes in organisational learning (Mittal et al., 2018).

2.3.3. Smart contracts

SMEs often lack contract frameworks (Villa and Bruno, 2013), which increases uncertainty and reduces trust — a necessary precondition for collaborations (Guo-Qiang, 2006). Several authors have described smart contracts based on distributed ledger technologies as a potential remedy (Buterin, 2014). Smart contracts encompass automated ordering, negotiations, shipment, and payment processes with parameters adapted to changing conditions (Ivanov et al., 2019). Beyond increased efficiency, the improved traceability, transparency, and consistency of ordering and contracts across the supply chain reduce uncertainty levels among partners (Müller et al., 2020; Schmidt et al., 2022). If partners feel that a transaction is equally transparent and verifiable for everyone involved through digital technologies, transaction-centred supply chains can be expected to evolve into cooperation-oriented ecosystems (Benitez et al., 2020; Papert and Pflaum, 2017; Schmidt et al., 2020; Schmidt et al., 2022).

2.3.4. Supplier development programs

Supplier development is a systematic approach to improving capacity and capability across the supply chain (Bai and Sarkis, 2019). While indirect supplier development involves setting performance goals and promising future business based on goal attainment, direct supplier development includes human-specific and capital-specific initiatives, such as training and providing equipment or finance to suppliers (Tran et al., 2021). Direct supplier development creates a fruitful ground for demand-driven collaboration, including supplier networking and matchmaking (Götz and Jankowska, 2017). A prominent example of such supplier development is *Virtuelle Fabrik* (virtual factory), an organised regional manufacturing network in Switzerland that supports short-term cooperative technological innovation efforts (Katzy and Crowston, 2008). In addition, managers in SME clusters act as innovation orchestrators by facilitating SMEs interaction (Batz et al., 2018), providing access to knowledge (Götz and Jankowska, 2017), problem-solving (Hoffmann et al., 2014; Niu, 2010), and making connections to external markets (Villa and Taurino, 2018).

2.4. Manufacturing ecosystems

2.4.1. Definition

The term 'ecosystem' is derived from biology, capturing a system of entities interacting and depending on each other and reacting to outside challenges and requirements (Basole, 2009). Business ecosystems represent the intense relationships between interlinked multilateral, complementary actors or partners which must interact for value creation (Adner, 2017; Jacobides et al., 2018). Ecosystems in their early stages are called *nascent ecosystems*, characterised by 'unclear product definitions', 'rapidly changing innovation', 'uncertainty about potential rivals', and the need for new partners for potentially unavailable components (Hannah, 2015; Hannah and Eisenhardt, 2018). Nascent ecosystems typically experience dynamic changes in their level and type of innovation (Hannah, 2015; Santos and Eisenhardt, 2009). These changes draw the attention of new customers, launching a reinforcing loop of ecosystem development by collaborative suppliers responding to customers' calls (Parker and Van Alstyne, 2005; Rochet and Tirole, 2003).

2.4.2. Theoretical framework

Jacobides et al. (2018) distinguish three generic types of ecosystems: Producer-Based, Platform-Based, and Multisided platform ecosystems. Their members can follow either system, component, or bottleneck strategies, where the latter is most attractive and profitable (Hannah and Eisenhardt, 2018). Our theoretical framework integrates these literature streams for manufacturing, explicitly focusing on the role of demand-driven SME collaborations (Fig. 1). Traditionally, OEMs follow a *system strategy* by orchestrating independent firms as their suppliers and providing a legal framework for work allocation. SMEs follow a *component strategy* by providing semi-parts for multiple supply chain tiers. For example, in the producer-based ecosystem, large Tier-1 suppliers are dominant; they cover the procurement gaps and capture the most profits, while SMEs experience lower utilisation rates (Kazantsev et al., 2022). Before supporting demand-driven collaboration, Tier-1 suppliers capture the most profitable orders and are hardly replaceable (a *bottleneck strategy*). Supporting the ecosystem with collaboration enablers increases the likelihood that SMEs would be able to compete for

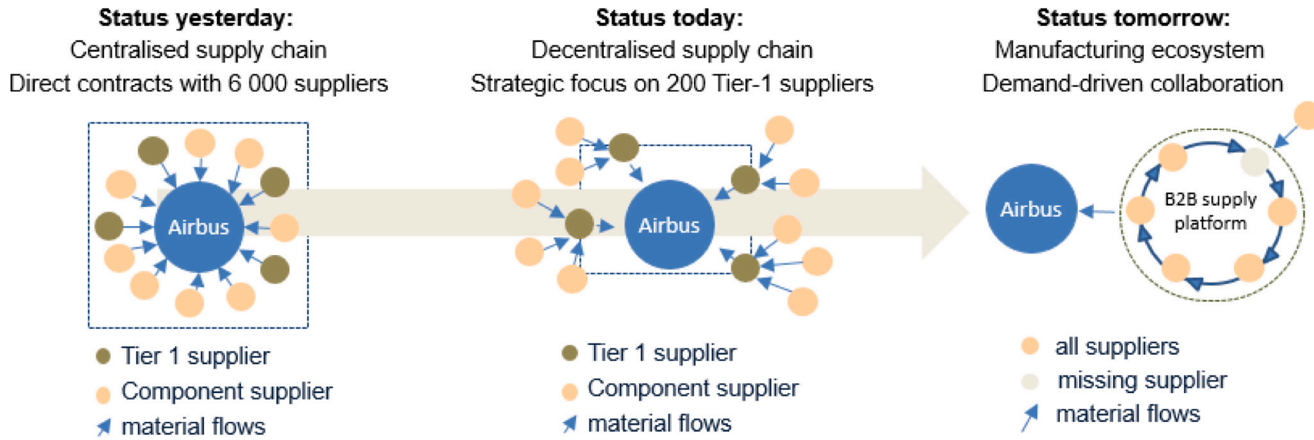


Fig. 2a. Airbus's refocusing has triggered changes in the aerospace industry (DIGICOR, 2023).

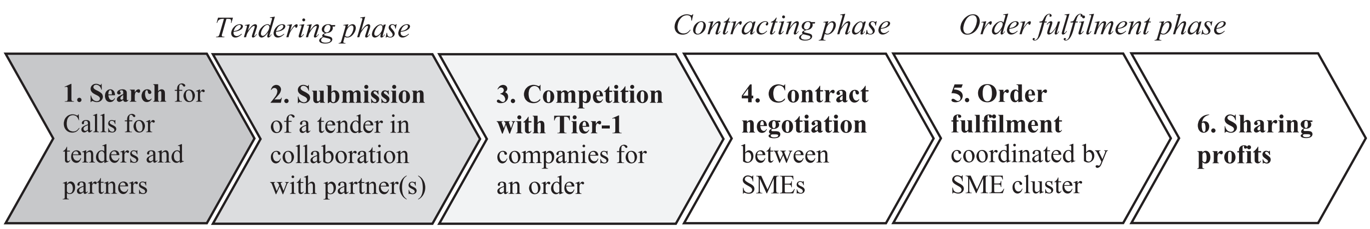


Fig. 2b. The exemplary process of tendering and order fulfilment in the aerospace industry, from the perspective of an SME.

orders with Tier-1 s, while OEMs would share order fulfilment risks between multiple suppliers.

3. Methodology

3.1. Case study

The aerospace industry is characterised by many SMEs and supplier collaboration challenges (Turkina et al., 2016). For the case study, we investigate the supply chain of the largest European aerospace manufacturer, intending to support demand-driven SME collaboration. In recent years of supply chain optimisation, Airbus has reduced direct supply relationships with >6000 multi-tier suppliers in favour of larger suppliers (Bernhard et al., 2007; Janke et al., 2007; Rossen et al., 2015). These changes have further reduced SMEs' ability to act as suppliers (Schirrmann and Drat, 2018) and exposed vertical supply chains to the risks of fluctuating demand. Fig. 2a illustrates the changing situation in aerospace supply chains; here, OEMs, such as Airbus, intend to increase

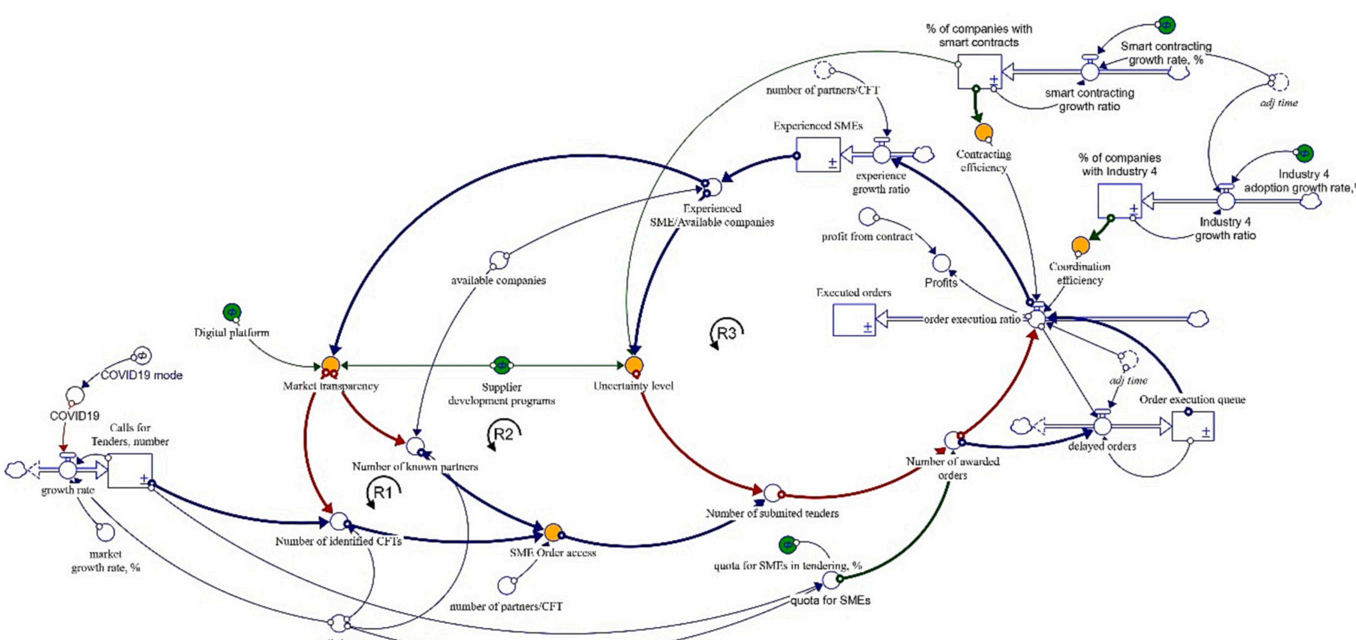


Fig. 3. Stock and Flow diagram of the manufacturing ecosystem.

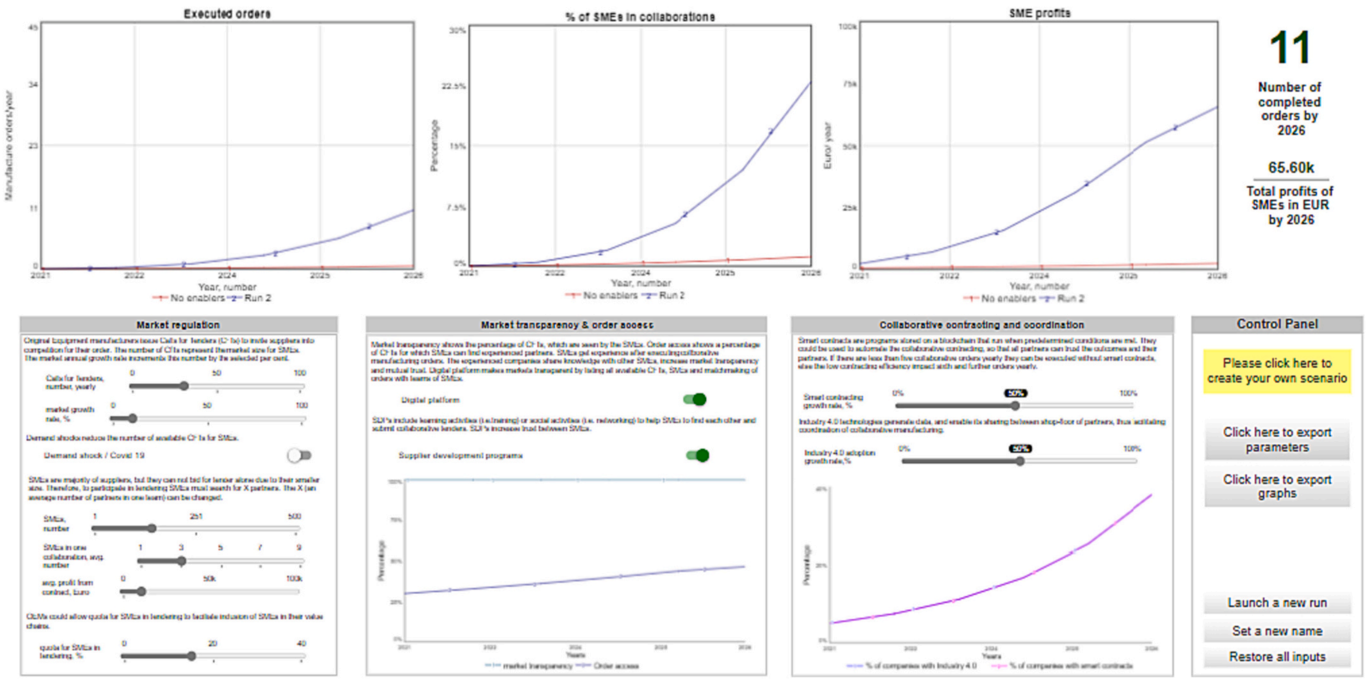


Fig. 4. The interactive dashboard was used for user interaction and testing.

the number of SME collaborations to support order fulfilment during demand changes.

An exemplary supplier cluster aggregates a broad spectrum of suppliers (about 140 companies) and is interested in supporting its members in collaborating on order fulfilment. For example, SME manufacturers and service providers can share generic producing capacities (turning, drilling, and milling) and increase production volumes for their OEM in sourcing product components. Following Faustino et al. (2019), we consider SMEs from the same supply cluster as ideal candidates for the sample since they have geographic proximity - an essential precondition for demand-driven collaboration.

The aerospace supply chain starts with the OEM, which places orders in a 'Calls for Tenders' (CfTs) document and disseminates the copies among Tier-1 suppliers. Tier-1 suppliers invite sub-contractors to supply sub-assemblies and services, often avoiding SMEs. Therefore, to find a potential manufacturing order, SMEs must search for CfTs and potential partners (other SMEs) themselves (Cisneros-Cabrera et al., 2021; Liu et al., 2022). Then, a team writes and submits a collaborative tender. The OEM compares all submitted tenders (including the bids from larger [tier-1] companies) and determines the recipient of a manufacturing order. Further, a lead SME negotiates the shared contract with the OEM and their partners. Finally, the team proceeds with order fulfilment and share profits after delivering the order. Fig. 2b visualises these six steps.

3.2. System dynamics

System dynamics is a method for understanding complex systems' nonlinear behaviour over time by modelling the key feedback loops (Sterman, 2000, p. 158), which applies to problems in complex social, managerial, economic, or ecological systems (Jahangirian et al., 2010; Richardson, 2011; Vidgen et al., 2017). Any model consists of stocks (rectangles), variables (circles), and connectors (arrows). Stocks accumulate the values according to the value distribution functions specified in each variable. Connectors depict the movement and transformation of values between the stocks. For example, a part of Calls for Tenders first becomes Submitted Tenders, then Awarded Orders, and finally Executed Orders (Fig. 3).

3.2.1. Stocks (rectangles)

The aerospace market growth rate (in %) influences the number of CfTs available yearly.[3] The number of SMEs that gain experience through the year (experience growth ratio) depends on the number of executed orders (order execution ratio) and the number of companies per collaboration (number of partners per CfT). Experienced SMEs represent companies that completed their collaborative order. The Order execution queue comprises the delayed orders that will be executed next year.

3.2.2. Barriers to demand-driven collaborations (orange circles)

Orange circles represent barriers to demand-driven collaboration between SMEs as identified in a previous study (Kazantsev et al., 2022): the lack of (i) market transparency, (ii) order access, (iii) trust (quantified as uncertainty level), (iv) contracting efficiency, and (v) coordination efficiency. Their impacts affect the following variables: the number of identified CfTs, known partners, submitted tenders, and order execution ratio.

3.2.3. Enablers (green circles)

Four enablers reduce these barriers: (1) supplier development programmes; (2) digital platforms; (3) smart contracting growth rate, and (4) Industry 4.0 adoption growth rate (Kazantsev et al., 2022). All four enablers are described in Section 2.4. A further enabler not described in Section 2.4 is a quota for SMEs that is further implemented via the variable percentage quota for SMEs in tendering.

3.2.4. Connectors (arrows)

To better visualise the model, we use several colours and arrow thicknesses. The standard connectors are blue and thin; the blue and bold arrows represent the key feedback loops in the system. Red arrows signify the identified bottlenecks due to the barriers, whereas green arrows indicate the positive impact of enablers to reduce a barrier (which causes a bottleneck). Finally, two stripes on an arrow signify the

[3] We added 'Covid-19 mode' to demonstrate a demand shock that drastically reduces the number of Calls for Tenders and triggers subsequent demand recovery over the following years

delay in an effect.

3.3. Model validation

First, we used openly accessible secondary data, such as the reports from the EU-funded DIGICOR project and aerospace industry reports, websites, and our interaction with SMEs along aerospace supply chain to draft the initial model (Akkermans and Van Wassenhove, 2018). Then, we validated this model with industrial experts, who proposed any changes they considered appropriate. Second, the model was presented twice at the System Dynamics Conference (2020–2021), and the experienced system dynamics society members gave expert guidance. Third, the lead author actively participated in open SD modelling sessions. Here, interdisciplinary scholars provided model feedback using system dynamics as their primary research method. Fourth, an interactive dashboard has been developed,[4] following the MIT En-Roads project sample (Fig. 4).

This dashboard enables end-user interaction with the simulation results without prior knowledge of system dynamics. Furthermore, the dashboard was used (a) to test simulation in other industries, such as the healthcare and food sectors, which provided additional scenarios of various ecosystem development (Kunc and O'Brien, 2017); (b) for teaching purposes in the course 'Digital platforms and Ecosystems', when the students actively simulated ecosystem growth under various conditions. Finally, the model has been analysed by two system dynamics experts with 30+ years of experience in SD modelling. All the feedback received during these sessions has been incorporated into the current version of the model.[5]

4. Manufacturing ecosystem modelling

4.1. Search for Calls for Tenders and partners

First, SMEs try to recognise potential manufacturing orders (The number of identified Calls for Tenders), depending on market transparency. For example, in a market with 50 Calls for Tenders and 10 % transparency, they can identify only five CfTs (1).

$$\text{The number of identified Calls for Tenders} = \\ \textit{Calls for Tenders}^{*}\ \textit{Market transparency}^{*}\ \textit{adj time}/100 \tag{1}$$

Two enablers can increase market transparency for SMEs supplier development programmes add 30 %; digital platforms – 100 % (Cisneros-Cabrera et al., 2021). However, each SME also needs partners to match the scale of this CfT. Hence, the model defines the variable 'SMEs access to order', which indicates the number of supplier teams that match the scope of CfTs' requirements this year (2).

$$\begin{array}{c} \textit{SME}\ \text{access to orders} = \\ \textit{IF Number of identified CFTs} * \textit{number of partners/CFT} <= \\ \textit{Number of known partners} \\ \textit{THEN Number of identified CFTs} \\ \textit{ELSE Number of known partners /number of partners/CFT} \end{array} \tag{2}$$

4.2. Submission of a tender in collaboration

Further, to write an submit a tender in a collaboration,[6] partners consider their confidence in partners, and market uncertainty. Should they collaborate if they feel a competitive threat? Or is there any other concern about future collaborative work? We formulate the uncertainty level based on the ratio of experienced SMEs (collaboration experience) in the manufacturing ecosystem, the application of supplier development programs and smart contracts (3).

$$\begin{array}{c} \text{Uncertainty level} = \\ \textit{IF}\ 100 - (\textit{Experienced SME/Available companies}/100 \\ + \%\ \textit{of companies with smart contracts}/100 \\ + \textit{Supplier development programs} * 0.3) * 100 >= 0 \\ \textit{THEN}\ 100 - (\textit{Experienced SME/Available companies}/100 \\ +\%\ \textit{of companies with smart contracts}/100 \\ + \textit{Supplier development programs} * 0.3) * 100 \\ \textit{ELSE}\ 0 \end{array} \tag{3}$$

The level of uncertainty in the ecosystem reduces the number of tenders accessible to SMEs (2), thus determining the number of submitted tenders (4). For example, if the uncertainty levels are 60 %, this percentage of tenders is left not submitted for competition.

$$\text{Number of submitted tenders} = \textit{SME Order access}^{*}\ (\textit{1–Uncertainty level/100}) \tag{4}$$

After receiving all tendering documentation, an OEM examines their fit for the purpose, compares the alternatives, and awards an order to the best bid (The number of awarded orders to SMEs), measured yearly. If the bids from larger companies overshadow the bids from SMEs, the latter can win orders only having a quota (5).

$$\text{The number of awarded orders} = \textit{MIN}\ (\textit{Number}\ \text{of submited tenders},\ \textit{quota}\ \text{for SMEs}) \tag{5}$$

4.3. Contract negotiation and order fulfillment

The selected team will fulfil the order under strict contract conditions regarding quality, time, and cost. However, the partners need to agree on all clauses of a collaborative contract; for example, the debates around certification and tax are likely between companies that are located in different countries or continents. Hence, delays are possible and can impede collaboration at this stage (Contracting efficiency), which can be improved by smart contracting. The more companies use smart contracts, the less time will be spent on negotiations and defining legal clauses (Contracting efficiency (6)). Industry 4.0 can improve data sharing, making it easier to fulfil collaborative orders in time (Coordination efficiency (7)).

$$\text{Contracting efficiency} = \%\ \textit{of}\ \text{companies with smart contracts} \tag{6}$$

$$\text{Coordination efficiency} = \%\ \textit{of}\ \text{companies with Industry}\ \textit{4.0} \tag{7}$$

The model stipulates that the clusters of SME (like the one analysed in the case study) can support coordination of not more than five orders annually. It means that the orders above the fifth awarded to its members anually, will being delayed until the following year. Order fulfilment will improve with Industry 4.0 tools for coordination, which allows the execution of all orders in the same year (8).

[4] https://exchange.iseesystems.com/public/mustermann/system-dynamics-of-nascent-ecosystem (accessed 10 September 2023)

[5] https://exchange.iseesystems.com/public/mustermann/system-dynamics-of-nascent-ecosystem (accessed 28 January 2023).

[6] From the pool of manufacturing orders that SMEs have access (SME access to orders)

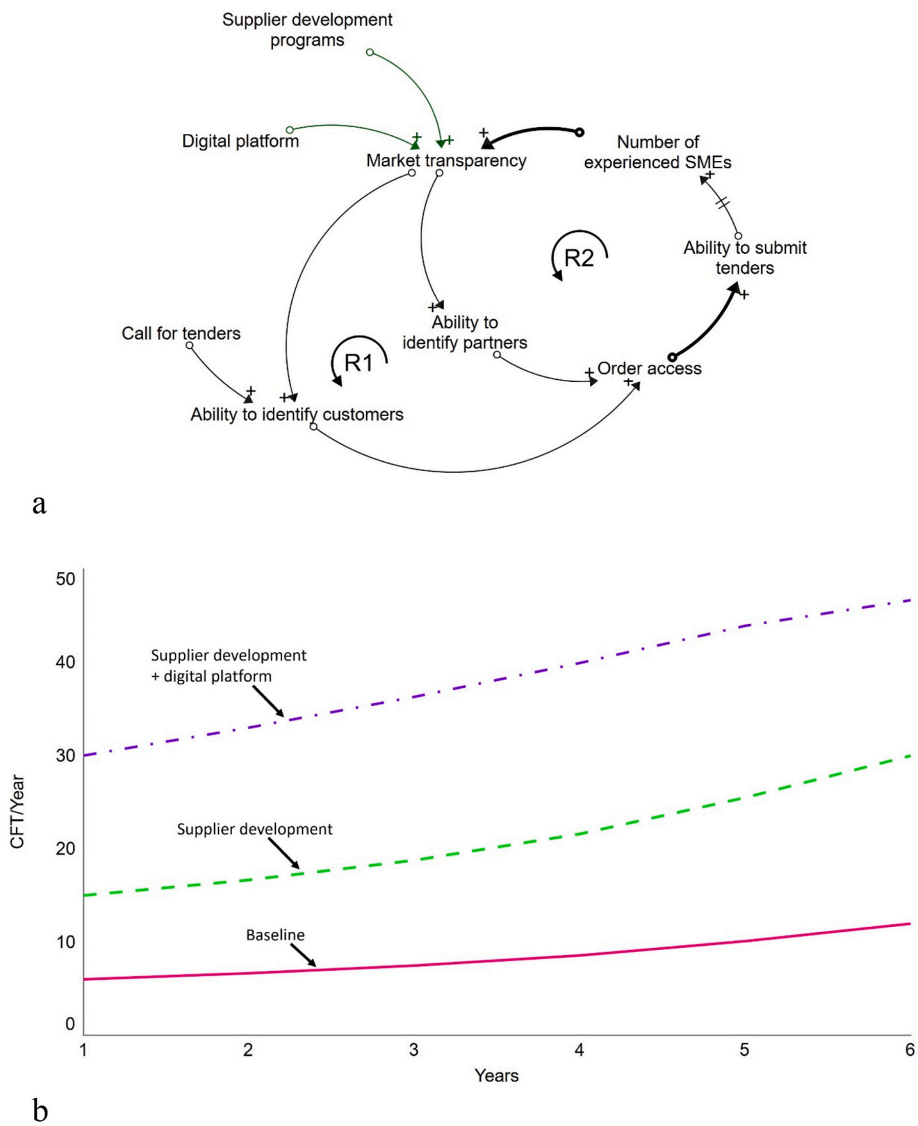


Fig. 5a. Reinforcing loops R1 and R2 leads to market transparency and order access. Bold arrows show the main impacts: the experience of SMEs and order access. b. Supplier development and digital platforms drive reinforcing loops to SME order access.

$$\begin{gathered}\text{The number of executed orders} = \\ IF\ (Number\ of\ awarded\ orders + Order\ execution\ queue * adj\ time) * \\ Contracting\ efficiency\ <= 5 \\ THEN\ (Number\ of\ awarded\ orders + Order\ execution\ queue * adj\ time) * \\ Contracting\ efficiency \\ ELSE\ 5 + ((Number\ of\ awarded\ orders + Order\ execution\ queue * adj\ time) * \\ Contracting\ efficiency - 5) * Coordination\ efficiency\end{gathered} \tag{8}$$

The formula (9) includes all non-completed orders from the previous years as they have been delayed.

$$\begin{gathered}\text{The number of delayed orders} = \\ IF\ Number\ of\ awarded\ orders\ -\ order\ execution\ ratio\ >=\ 0 \\ THEN\ Number\ of\ awarded\ orders\ -\ order\ execution\ ratio \\ ELSE\ MIN\ ((Number\ of\ awarded\ orders\ -\ order\ execution\ ratio), \\ Order\ execution\ queue\ *\ adj\ time)\end{gathered} \tag{9}$$

Finally, the model enables the reinforcing loop of collaboration experience in SMEs (The experience growth rate) caused by successfully fulfilling orders, capturing profits and gaining collaboration experience (10).

$$\begin{gathered}\text{The experience growth rate} = \\ IF\ order\ execution\ ratio\ *\ number\ of\ partners/CFT\ <=\ 0 \\ THEN\ 0 \\ ELSE\ order\ execution\ ratio\ *\ number\ of\ partners/CFT\end{gathered} \tag{10}$$

5. Manufacturing ecosystem growth: Causal loops and simulation

The case study includes 140 SMEs in the supplier cluster, that require support for demand-driven collaboration. Based on the interview quotes, we developed the following scenario:

- There are 20 % of experienced firms (28 in total) in the SME cluster of 140 companies
- An average demand-driven collaboration consists of three companies, one of which is usually an experienced partner (the SME Lead)
- 30 Calls for Tenders (CFTs) are available yearly, which also grows 10 %
- The market uncertainty level is 45 %
- SME Cluster runs supplier development programs and uses a digital B2B platform

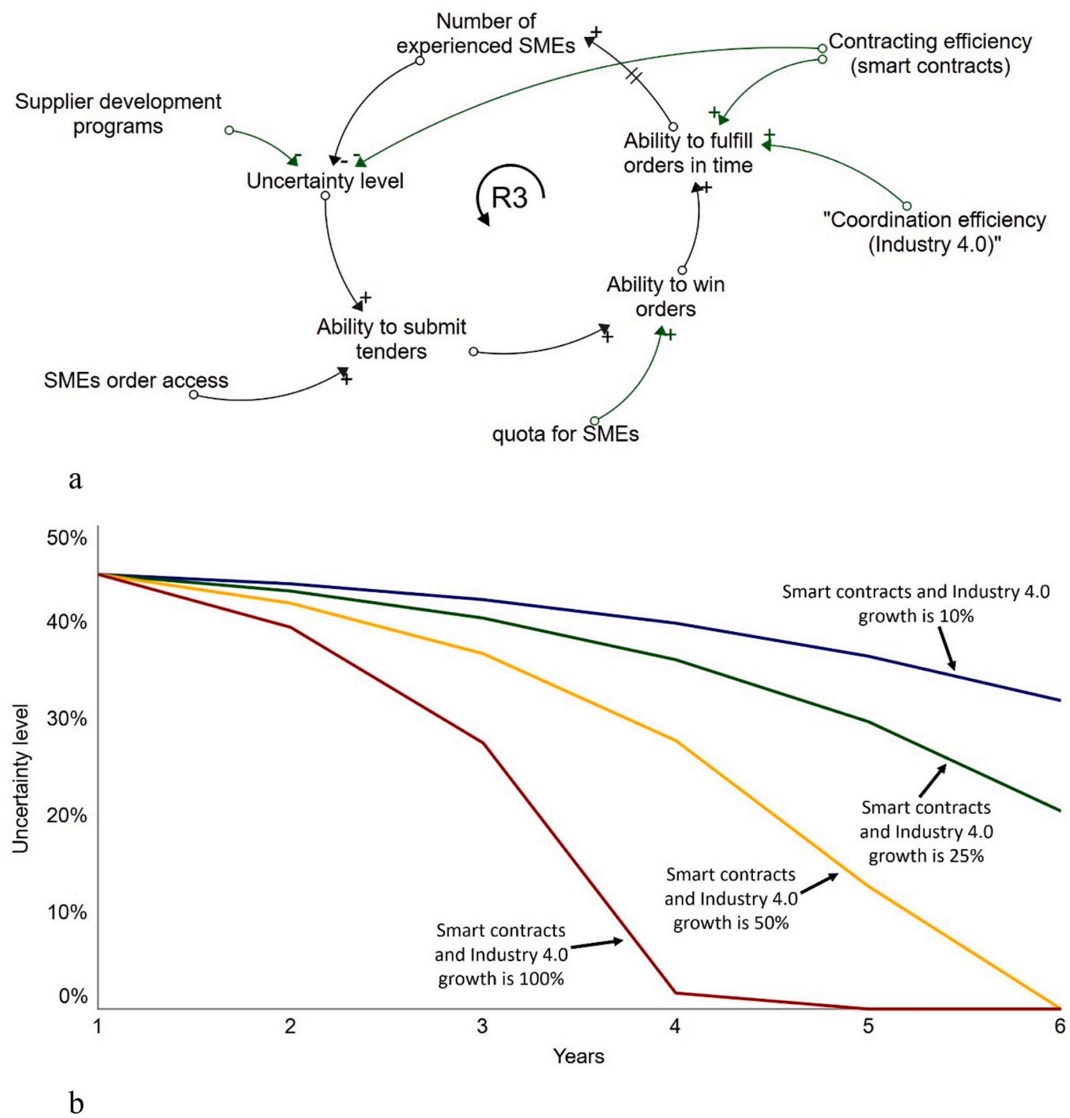


Fig. 6a. Smart contracting and supplier development programs reduce uncertainty b. The removal of uncertainty in time.

- The OEM stipulates a quota for SMEs in tendering (15 %)
- Supported by the national digitalization program, OEMs and SMEs co-invest in smart contracting and Industry 4.0 for SMEs by 25 and 50 % annually (two scenarios), starting at 5 %.

5.1. Search for Calls for Tenders and partners

First, the ecosystem orchestrator initiates *supplier development programmes* and the development of a *digital platform* to help SMEs identify more calls for tenders (R1) and partners (R2). SMEs learn how to collaborate and increase their chances of forming teams. The rise of the collaboration experience makes the marketplace more transparent (Fig. 5a, 5b).

Simulation outcome: Supplier development and digital platforms make marketplaces more transparent so that SMEs can see more manufacturing orders.

5.2. Submission of a tender in collaboration

The more firms collaborate on tenders, the lower the level of market uncertainty. New technologies, such as smart contracting increase the number of submitted tenders (Fig. 6a, 6b).

Simulation outcome: The collaboration experience and smart contracts reduce uncertainty levels and enable supplier teams to submit more collaborative tenders.

5.3. Contract negotiation and order fulfillment

The integrated causal loop diagram (Fig. 7a) demonstrates *four key feedback loops* that trigger the formation of manufacturing ecosystems. As in the initial stages of ecosystem formation, supplier teams cannot win tenders against Tier-1 suppliers, a quota is required to support them in getting collaboration experience (Fig. 7b). A quota enables SMEs to win orders but execute them slower due to insufficient contracting and coordination efficiency.[7] Adopting smart contracting and Industry 4.0 increases the number of awarded orders executed in time, increasing the pace of manufacturing ecosystem growth (Fig. 7c). Specifically, if orchestrators double their investments into smart contracting and Industry 4.0 every year, the number of delayed orders grows until the 5th year but then starts falling. In the 6th year, 48 calls for tenders will be

[7] Industry 4.0 is required to support collaborative order execution (9).

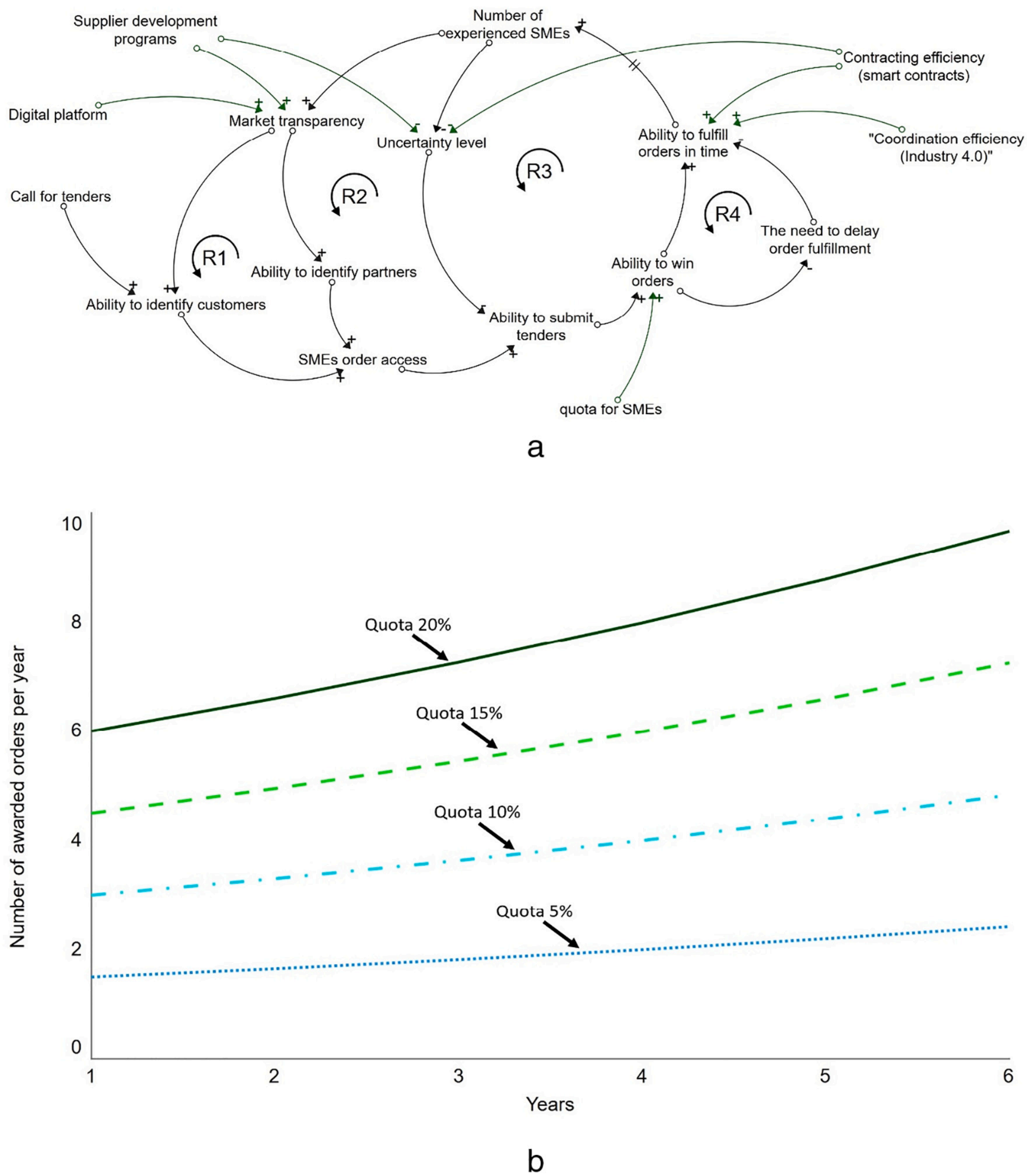


Fig. 7. a. Causal loop diagram of the manufacturing ecosystem.
b. The number of awarded orders with the quota for SMEs is 5 %, 10 %, 15 %, or 20 %.
c. The number of executed orders (CFTs) depending on investment into digitalisation.
d. The number of executed orders, order execution queue, and order execution ratio.

available, with a 15 % quota, seven orders out of which will be fulfilled the same year, and six orders from the previous year's queue. In this case, the order execution rate reaches a plateau - executing all awarded orders. Fig. 7d shows that Year 5 as a breakeven point when order execution rate, delayed, and executed orders intersect.

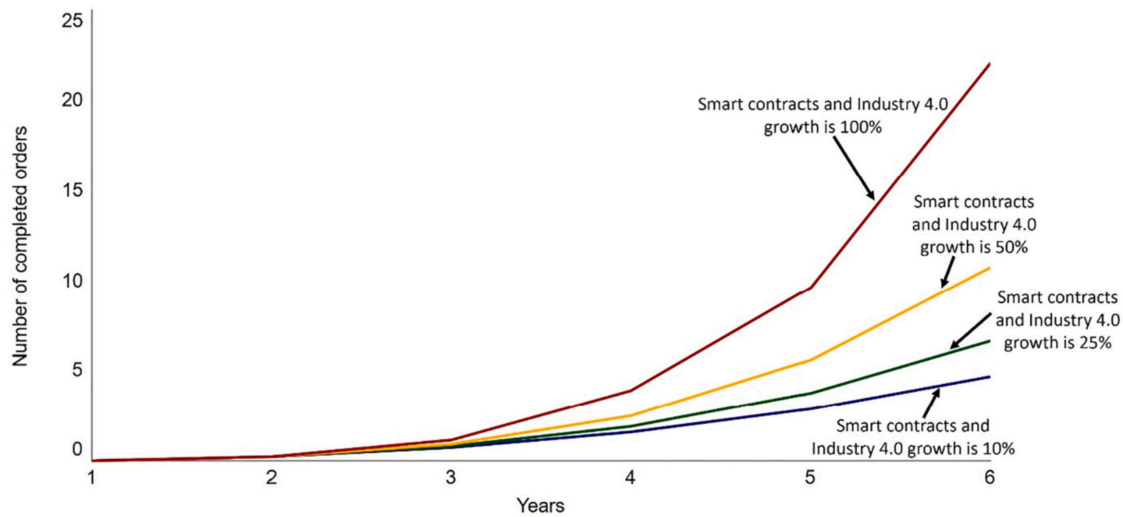
Simulation outcome: Technological support for contracting and coordination reduces the order execution queue and supports the growth of a manufacturing ecosystem.

6. Discussion and conclusion

This paper addresses the shortage of studies on methods to facilitate demand-driven collaborations between SMEs (Müller et al., 2018; Schmidt et al., 2020) and envision the impact of such collaborations on manufacturing ecosystem growth (Ferrell et al., 2020). By analysing various collaboration enablers, we elucidated how they affect the system dynamics of supply chains and encourage a shift towards manufacturing ecosystems. Once companies start winning tenders and fulfilling orders, their learning curve enables further ecosystem development with less dependency on manual orchestration.

6.1. Theoretical contribution

This paper extends extant findings on shifts from a supply chain to an ecosystem level (Georgiadis and Michaloudis, 2012; Russell and Smorodinskaya, 2018; Jacobides et al., 2018) and literature on platform-



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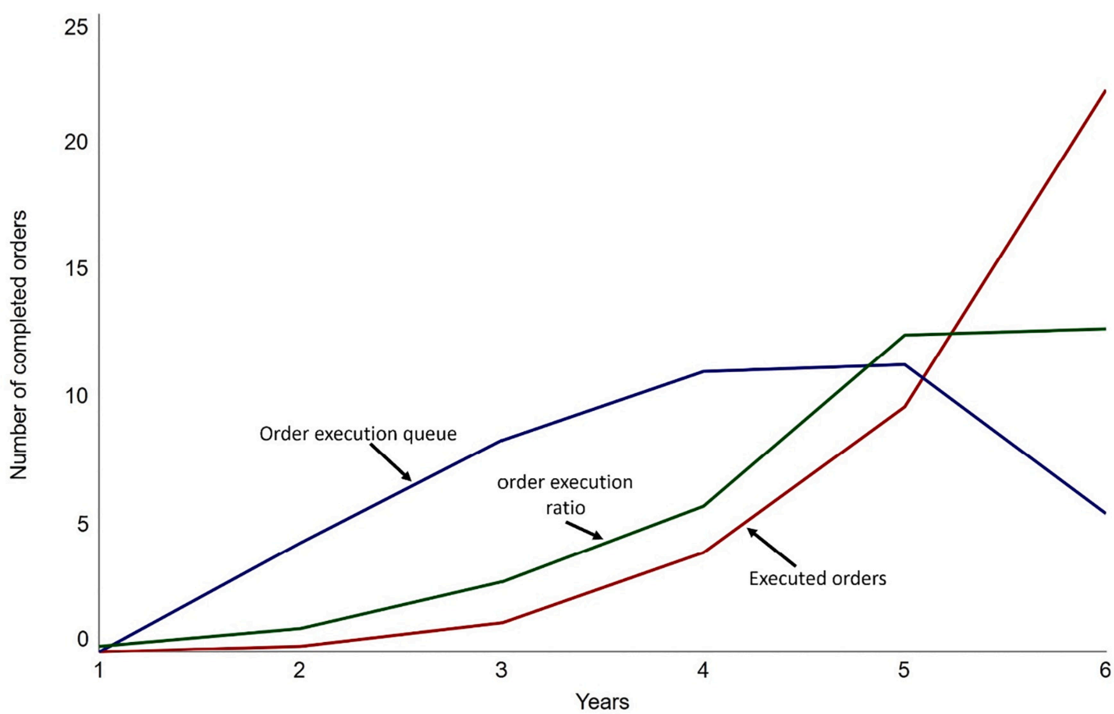

d

Fig. 7. (*continued*).

driven supply chain collaboration (MacCarthy et al., 2016). Particularly, we contribute to the research on nascent ecosystems (Hannah, 2015; Hannah and Eisenhardt, 2018; McDonald and Eisenhardt, 2020) and to research on manufacturing ecosystems driven by Industry 4.0 (Benitez et al., 2020; Papert and Pflaum, 2017; Schmidt et al., 2020). The system dynamics model reveals the advantages of manufacturing ecosystems, as OEMs can increase sourcing and share risks using smaller suppliers. In turn, SMEs increase their utilisation rate, gain collaboration experience, and contribute to the local economy.

6.2. Methodological contribution

Using system dynamics, we provide a methodological contribution to the ongoing discussion initiated by the special issue, 'How can SD and AI simulations provide an understanding of innovation and eco-innovation systems'? Our manufacturing ecosystem model argues for the conditions leading to demand-driven collaboration and innovation (e.g., capacity sharing, knowledge exchange, new product development). The present model can produce initial training datasets for AI and ML algorithms, demonstrating the long-term impacts of demand-driven collaboration on ecosystem development.

6.3. Managerial and policy implications

The paper provides evidence for policymakers (such as the European Commission) about the role of demand-driven SME collaboration in unfolding manufacturing ecosystems and the need to support SMEs using the proposed enablers, which is expecially needed for the early stages of ecosystem development. The system dynamics perspective emphasises the importance of (1) investing in supplier development and digital platforms as early as possible to make manufacturing marketplaces transparent; (2) enabling quotas for SMEs in tendering to allow smaller firms access tendering to gain collaboration experience; and (3) increasing digitalisation of conventional contracting and coordination mechanisms to support the efficiency of demand-driven collaborations.

6.4. Limitations and future work

The system dynamics model was built using an aerospace manufacturing case study, considering the intention of SMEs to adopt enablers of demand-driven collaboration. While the current model describes the conditions of capacity sharing between SMEs producing the same components, it does not explore manufacturing scenarios where SMEs produce complementary parts of a complex product. Further, due to information security requirements, some strongly regulated industries might remain restricted in a traditional supply chain organisation, such as the defence sector. The whole regions where specific sectors are intensely regulated and hierarchically controlled, may deny the ecosystem as a strategy. It is also unclear how to measure trustworthiness to a partner, especially how it relates to participation in supplier development programmes. Finally, political stability and the rule of law are necessary for the suggested business transformations.

While the results can be transferred to other manufacturing industries, a more complex view of collaboration between buyers and suppliers with different products or services represents a fruitful area for future research (e.g., the new product development, the impacts of public policy, industry associations [which allow recognition of the community members], and certifications [that give the holder an accreditation of specific competence]). Negative scenarios of manufacturing ecosystem growth are also to be considered, especially the conditions of ecosystem failure, critical flaws in distributed production or information security risks. Specifically, the financial impacts of order execution and profitability should be explored in more detail, as the authors of this work do not possess the data to calibrate the model to control for revenues and investments. Another potential follow-up study is to open a manufacturing ecosystem for other actors beyond aerospace manufacturing. The potential participants include insurance companies, data science, and software development firms. Finally, the following papers should consider the role of non-traditional suppliers in supporting manufacturing ecosystem growth.

CRediT authorship contribution statement

Nikolai Kazantsev: Conceptualization, Methodology, Data Curation, Formal analysis, Writing – Original Draft.

Oleksii Petrovskyi: Research Method & Validation, Review & Editing.

Julian Muller: Supervision, Review & Editing.

Data availability

Data will be made available on request.

Acknowledgements

The first author acknowledges the EU-funded project DIGICOR (grant agreement no. 723336) that developed one of the enablers of demand-driven collaborations — an ontology-guided digital B2B platform (Cisneros-Cabrera et al., 2021; Cisneros-Cabrera et al., 2018). The first author is grateful to Prof. Nikolay Mehandjiev, Dr. Pedro Sampaio, and Dr. Grigory Pishchulov for PhD supervision at the University of Manchester (Kazantsev, 2022) and wishes to acknowledge the help of Ingo Martens and Arnd Schirrmann (HANSE Aerospace). We thank the organisers of the 6th World Conference on Production and Operations Management (P&OM Nara 2021), particularly Prof. Jan Godsell, for organising a session on manufacturing ecosystems, which enabled the presentation of an early version of this paper. Further, the first author acknowledges ESRC Made Smarter Network+ ('InterAct') J17293 for received early-career fellowship, and declares that this work was supported by the UKRI Made Smarter Innovation Challenge and the Economic and Social Research Council via InterAct [Grant Reference ES/W007231/1]. Further, the first author thanks the grant EP/T024429/1 via 'Elastic Manufacturing systems – a platform for dynamic, resilient and cost-effective manufacturing services'. Finally, the first author appreciates the friendly reviews of Dr. Fabio Neves da Rocha (Edinburgh Napier University) and Dr. Fathiro Putra (Institute for Manufacturing [IfM], University of Cambridge) that increased the manuscript's quality.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techfore.2023.122917.

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