

## Supply Chain Digital Twins: Opportunities and Challenges Beyond the Hype

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### Abstract

This paper discusses the application of digital twin concepts, prevalent in the factory unit operations environment, to the supply chain context. While the concept of digital twin is relatively recent in the manufacturing context, its application has now emerged within a wider supply chain context. It is unclear in this broader application what might the benefits of such an approach be in terms of operational control, replicability and efficiency. Following a literature review, the attributes of a Digital Twin Supply Chain (DTSC) are defined, highlighting similarities and differences from the traditional factory perspective that places the emphasis on equipment and unit operations. Selected DTSC attributes are then applied within a selection of industry case studies where advanced manufacturing technologies and industrial digitalisation are expected to provide new capability in terms of more distributed made-to-order manufacturing (e.g., in pharmaceuticals supply chains), as well as enhanced visibility, traceability and authentication (e.g., in organic food supply chains).

Keywords: Digital Twin; digitalisation; supply chain; pharmaceuticals; food

### 1. Introduction

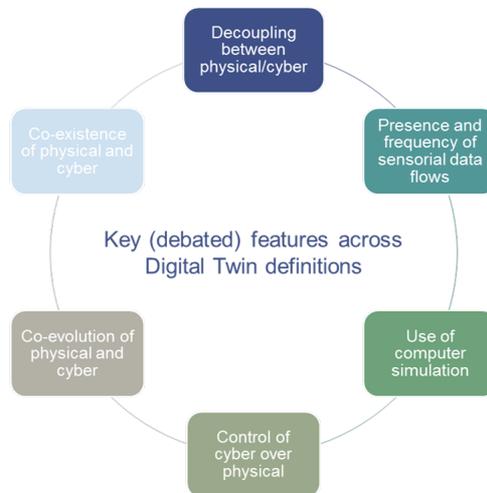
It is becoming a commonly held view that digital connectivity, computing power and manufacturing automation will enable increasingly autonomous, self-organizing and integrated production systems linked together through seamlessly connected supply networks (World Economic Forum, 2018). Last year, the British government released up to £121 m for the Made Smarter programme, supporting the adoption of industrial digitalisation technologies (IDT) in manufacturing as part of a broader Industrial Strategy Challenge Fund (HM Treasury, 2018). Expectations towards a faster adoption of IDT in the UK are particularly high, with estimated benefits in the ballpark of £455 bn and 30% increase in manufacturing productivity by 2030 (Made Smarter Review, 2017).

Several aspects, however, point towards the possibility of a hype surrounding the digitalisation of manufacturing. Often, the institutional and industrial narratives depict the attainment of inter-organisational productivity gains through IDT as self-evident matter-of-fact. Even in the academic literature, concepts such as ‘self-thinking supply chains’ overtly suggest that the generation of large amount of data through connected, sensing objects suffice to make accurate predictions and take autonomous action beyond the boundaries of individual firms (Calatayud et al., 2019). Fewer works offer a conceptual critique of these apparently straightforward cause-and-effect relationships (e.g., Caruso, 2018). Concerns about the exaggeration of IDT, and the proliferation of confusing terminology were raised e.g., in the process industry (Saudagar et al., 2019).

In this context, it may be useful to distinguish between *asset-* and *supply chain-centric* perspectives on IDT:

- An *asset-centric* perspective places particular emphasis on hyper-connected, sensing objects equipped with some form of prescriptive ‘intelligence’. This brings about the need for an appropriate ‘virtual’ representation of physical objects – commonly referred to as ‘digital twin’ (Grieves and Vickers, 2017). Developments in this area focus on the architecture enabling communication between physical systems through which data is sensed, and ‘cyber’ layers processing such data e.g., Alam and El Saddik (2017).
- From a *supply chain-centric* perspective, interest in digital innovation and enhanced deployment of information is ultimately linked to understanding how variability in demand may be sensed, and production capacity adjusted accordingly, without compromising time-to-serve and avoiding excessive inventory (Liotine, 2020). While increasing the amount of shared information is generally regarded as leading to enhanced visibility, questions arise on whether such information should be accessible to humans to act upon it, not just to software triggering automated responses (Cortada, 2011, Ch.3).

This paper sets out to explore the often overlooked/oversimplified relationship between the above mentioned asset-centric and supply chain-centric perspectives on IDT, by taking a closer look at some of the challenges and opportunities of extending the concept of ‘digital twin’ prevalent in the factory unit operations environment, to a wider supply chain context. Following a literature review, possible attributes of a Digital Twin Supply Chain are defined. These attributes are conceptually evaluated with specific reference to a selection of industry test cases involving the adoption of advanced manufacturing technologies and/or industrial digitalisation, with applications in pharmaceutical and agri-food supply chains. The paper closes providing directions for future research.



**Figure 1.** Themes related to the DT concept arising in the reviewed literature, which may generate confusion.

## 2. Literature overview: conceptual and analytical challenges

The concept of digital twins (DT) originates in the field of Product Lifecycle Management (PLM) and mainly developed through the impetus of defence aerospace programmes – Tao et al. (2019) provide an overview. Regardless of the specific definition used, the DT concept typically involves the following aspects: 1) a physical object; 2) its ‘digital’ or ‘virtual’ representation; and 3) the nature of the connection between the two, as well as between DTs. In the Industrie 4.0 context, similar aspects may be referred to through adjacent concepts such as Cyber-Physical Systems (CPS) – for a review, see Ghobakhloo (2018).

Due to space constraints, providing a summary overview of the relevant literature on DT is beyond scope. However, one aspect that immediately stands out from the literature is the prevalence of an asset-centric perspective, with only one work elaborating beyond purely technical systems (Batty, 2018), and one work explicitly touching on the concept of digital supply chain twins (Ivanov et al., 2018). Disregard the perspective taken, applications are sparse, and the terminology used across the selected reference to express what a DT is varies considerably, with operational repercussions on what is expected from the implementation of such concept. Two alternative attitudes towards the nature of DTs vis-à-vis physical objects seem to emerge:

- 1) The former complement/describe the latter: a DT is interrogated to learn about its physical counterpart. Typical wording include ‘rich representation’, ‘digital proxy’, ‘software avatar’; or
- 2) The former must match exactly the latter a DT converges to, and merges with its physical counterpart. Typical wording include ‘mirror image’; and ‘exact replica’.

Figure 1 highlights some recurring themes around key operational aspects of a DT. Perhaps the most prominent of these themes is the extent to which DTs and physical objects are coupled. In particular, it is not always obvious which features of the ‘real’ system under scrutiny should be considered and to what level of abstraction. A view of DT as ‘mirror image’ suggests that all aspects of manufacturing assets in a factory must be captured (e.g., Bao et al., 2019). Such DT, if achieved, would be no different from what it aims to mirror, and therefore of little use for exploring and learning about it (Batty, 2018). Similarly, terms like ‘real-time’ may suggest no lag in updates between cyber and physical, and no need to sample sensor-data (e.g., Ghobakhloo, 2018). Closely related issues around the concept of DT arise considering the pervasiveness of cyber over physical: whether the former generates and communicates findings about the latter, or act upon it (e.g., Grieves and Vickers, 2017). At the same time, such terms as ‘co-evolution’ imply some impact of physical on cyber as the latter assumedly re-defines its own parameters as both go along (Cheng et al., 2018). If co-existence of physical and cyber is assumed, DTs may be of limited use for exploring alternative designs and scenarios. While there is no consensus on DT modelling, computer simulations appears to play a major role in conceptualising a DT (Tao et al., 2019), especially in the context of supply chains (Ivanov et al., 2018). Besides simulation, most quantitative approaches associated with DTs (optimisation, ‘advanced’ analytics, artificial intelligence, machine learning) are treated as self-explanatory.

## 3. Supply chain digital twins: attributes identification and potential application

The previous section showed that DT is a relatively recent concept, still characterised by some terminological ambiguity, and often associated with assumedly self-evident analytical capabilities. Manufacturing applications of DTs emphasise equipment and unit operations (e.g., Bao et al., 2019). When considering the wider supply chain context, a DT is often equated with capabilities assumedly available in specialised Supply Chain Network Design (SCND) and simulation tools (e.g., Ivanov et al., 2018). This section contributes to the debate by deriving relevant attributes of a Digital Twin Supply Chain (DTSC) from exploratory industry cases where advanced manufacturing

technologies and industrial digitalisation are expected to provide new capability. These cases, and the associated attributes are summarised in Table 1. More context is provided below.

**Table 1.** DTSC features, and preliminary applications across cases

DTSC attribute	Cases		
	Pharmaceutical	Organic food	Precision agriculture
<i>Ambitions</i>	Patient-centric performance & Inventory reduction	Consumer-centric transparency & Trust	Rural livelihood & resource stewardship
<i>Scope</i>			
Assets/product description	Predictive mechanistic models for micro factory continuous processing; Rich description of JIT clinical pharmacy	Biomarker & probing technologies linking data through to individual SKUs	software avatars: AGV and sensors to be emulated; specific crops
Unit ops	Batch vs continuous processing; Quality Assurance release; additive manufacturing; care pathways/patient engagement	Workflows/Quality assurance farm-to-fork; farming & food processing operations	Emulation of field operations AGV routing
Network Configuration	Semantic matching using digital supply chain Ontologies	Tracing; alternative sourcing decisions	Asset sharing and route to local markets
Multi-echelon inventory/service modelling	'Control tower' concept; more integrated channel management	Visibility from farmer, through processors to retailers	Align input resource acquisition with market demand
<i>Boundaries</i>	End-to-end: fine chem. to patient	End-to-end: farm to fork	Specific geography
<i>Infrastructure</i>			
Platform technology (indicative only)	e.g., SAP Hana	e.g., Siemens MindSphere	Framework only
Supply Chain Mapping tools	Bespoke mapping tools + SuperPro Designer (Intelligen) Witness (Lanner); Supply Chain Guru (Llamssoft); Umberto (IfU)	Bespoke mapping tool; Business Process Model Notation; Witness (Lanner)	Mostly bespoke + Witness (Lanner)
Digital data acquisition management	Mfg. 'data triggers'; Smart packs monitoring; patient wearables & mobile apps	Administrative linked to organic status; product physical properties	Crop water requirements; AGV position

### 3.1. Case 1: Pharmaceutical supply chains

The pharmaceutical sector is recently at the heart of collaborations between academia and industry, harnessing new technologies to develop a 'truly digital' supply chain. In particular, industry-led developments akin to the concept of DT have been facilitated as part of recently concluded UK-based research programmes, for example (Badman and Srail, 2018): 1) a digital factory demonstrator linked to a control tower software platform aimed at improving service and delivery for selected medicinal product lines; 2) a prototype of 'Just-in-Time' clinical pharmacy providing support to complex drug trials, while optimising the trade-off between shortage risk and investigational medicinal product waste; 3) advanced use of printed electronics in smart packs for product tracking and monitoring, and smart labels for patient engagement. Within the same initiative, a digital supply chain ontology (DiSCO) was developed to enable reconfiguration based on semantic matching of e.g. batch genealogy, product ontology and digital data streams enabled e.g. from smart package (Trokanas and Srail, 2017). It is argued that supply chain ontologies, while easily overlooked, provide the backbone of an implementable DTSC.

An asset-based perspective on DT characterises ongoing research in the area of continuous manufacturing of pharmaceuticals. Mechanistic models of continuous unit operations provide the necessary feedback to dynamically monitor and control a reduced-footprint physical process, or 'microfactory' (e.g., crystallisation, agglomeration, isolation, compression) while adapting to the latter's behaviour (CMAC, 2018). In this context, most opportunities for DT development lie in the ability to combine model-based and experimental evidence to explore and predict new product properties and continuous processing performance. When moving from a purely asset-centric to a supply-chain perspective on DT, key challenges concern the ideal design of more distributed networks enabled by modular, continuous microfactories – see Srail et al. (in press). The main difficulty in transitioning from DT to DTSC concerns the alignment between the level of granularity often available at the product and unit-operations level and what most off-the-shelf tools for SCND and inventory optimisation can handle, as these are typically agnostic with respect to the underpinning manufacturing technology.

### 3.2. Case 2: Organic food supply chains

Overcoming low consumer trust and enhancing transparency are key challenges in food supply systems design. With specific regards to organic food, consumers seek to make more informed choice, requiring convincing

evidence of the origin and organic status of produce such as meat and vegetables available on retailers' shelves. While extensive labelling systems for the identification and traceability of organic food exists, these do not guarantee, per se, that consumers can discern the organic qualification of individual products on retailers' shelves – especially meats (Ricke et al., 2012 Ch.1). As food frauds are perceived as a tangible threat to consumer trust in organic food, digital technologies and advanced chemical-analytical techniques are now regarded as promising means for the authentication of food production system. Using beef meat as an example, the former may include RFID technologies for tracking electronic product information (Liang et al., 2015); whereas examples of the latter include metabolomics approaches for the identification of specific biomarkers (Osorio et al., 2012).

Despite its potential relevance in the context described above, the concept of DT typically assumes long-life assets – rather than nondurable products such as food. Among the few exceptions is the development of a food product digital twin for use in the design of fruit and vegetables cold chain (Defraeye et al., 2019). Opportunities for further developments towards a DTSC in this context arise from the need to guarantee the integrity of organic food supply chains through open and transparent digitised platforms accessible to all participants, including final consumers. In the EU, mandatory information about relevant actors along the organic food supply chains is already digitalised to an extent: for example, local authorities provide web-based resources that can be readily interrogated to verify the organic status of specific food processors or farmers (e.g., [www.bioc.info](http://www.bioc.info)). However, practices currently vary across businesses (farmers, processors and retailers) in terms of required level of formalisation and automation when generating/retrieving the necessary information to ensure organic status from-farm-to-fork. Most verification workflows relying on manual checks of documental information, there is ample scope for a greater integration into such workflows of analytical information obtained from the rapid detection of biomarkers in organic products.

### 3.3. Case 3: *Precision agriculture in water stressed areas*

Unlike the case of food produce, the conceptual and architectural aspects of DTs have been more widely investigated in the context of mobility improvement through 'intelligent' autonomous vehicles - IAV (e.g., Alam and El Saddik, 2017). Fewer works however, attempt to introduce a supply chain-centric perspective, bridging the gap between fairly well understood DT of an IAV and its role in the broader context of a DTSC. In particular, Tsolakis et al. (2019) provide a framework as well as empirical evidence supporting the transition from simulation of physical IAVs, through three-dimensional validation and verification using emulation tools that take into account sensor-explore optimal intra-warehouse logistics design. This framework was further developed to support precision agriculture in water stressed areas as part of a wider programme aimed to inform the sustainable use of water and build resilience in Indian agri-food supply chains (<https://tigr2ess.globalfood.cam.ac.uk/>). In particular, the application of sensory-driven IAV provides a viable solution for the collection of data about crop's water requirements at different growth stages, providing targeted farming inputs and greater scope to automate harvesting operations. Key implications for the development of DTSC include real-time data capture enabled by automated applications, with particular value for the Indian agricultural context, and the ability to inform the development of more advanced farming decision support systems. Opportunities for the proposed synergistic use of sensory-driven IAV and their DT include enhanced economic viability of high-valued crops such as specific varieties of citrus fruits, and hence Indian farmers' livelihood, while contributing to improve the management of local freshwater resources. This is achieved through the concurrent design of the following DTSC elements: (i) Sensors utilised to enable context awareness in agrifield autonomous operations; (ii) Autonomous vehicles for inspecting the crop plantations and performing precision agriculture operations; (iii) Routing algorithms for navigating autonomous vehicles to optimise precision farming operations for high-value sustainable crops in terms of cost, time and efficiency; (iv) farmer/user engagement by capturing and operationalising sensor-data through mobile app interfaces, aimed at achieving a more informed role of farmers within broader supply network.

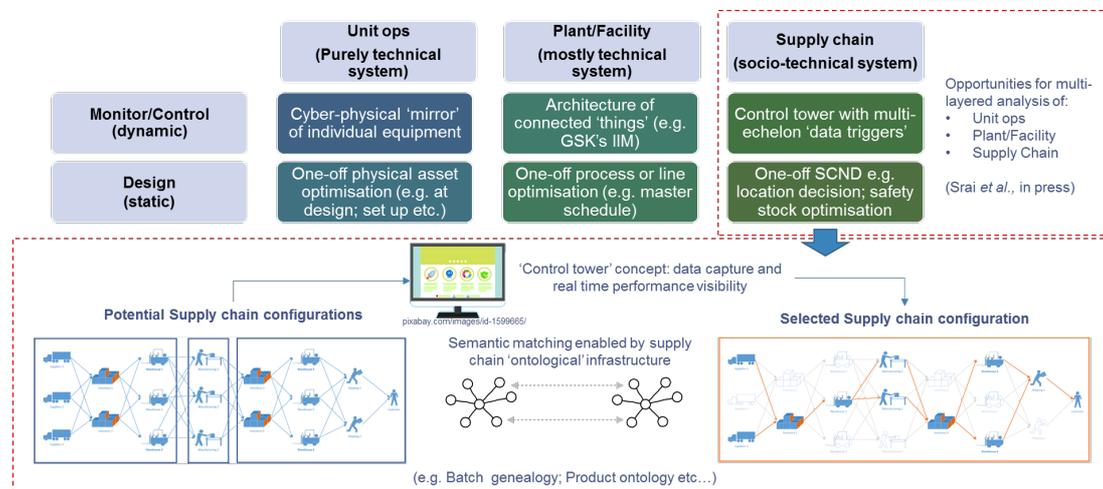
## 4. Discussion

In the previous section, possible attributes of a DTSC were highlighted, along with the associated opportunities arising from preliminary applications to industry cases developed as part of ongoing, or recently concluded collaborative research programmes. These opportunities and challenges can be summarised as shown in Table 2. In terms of opportunities, the cases presented here demonstrate ample scope for exploring the potential of DTs beyond specific equipment or factory boundaries, in the wider supply chain context. The chosen cases align well with exciting developments in asset-centric DT, in particular the concept of microfactory (Park et al., 2019); and distributed manufacturing models coupled with the use of 'blockchain' technologies in low trust environment (Mandolla et al., 2019). Unlike most literature, however, the challenges encountered in the cases discussed here are not purely technological, rather, they arise in trying to endow data with meaning, and putting the insights obtained in action: these challenges pre-exist the incumbent digitalisation narrative. In particular, the use of advanced information technologies and automation throughout the extended enterprise have been explored in adjacent fields e.g., Advanced Planning Systems - APS (e.g., Stadtler et al., 2015). Current conceptualisations whilst exciting do not elaborate on where existing approaches end and DTSC begins (e.g., Ivanov et al., 2018).

**Table 2** Identified opportunities and challenges for DTSC across cases

	Cases		
	Pharmaceutical	Organic food	Precision agriculture
<i>Opportunity</i>	Control tower approach for improved service/reduce inventory; re-configurability driven by changes in materials/processes/information.	Reliable organic authentication combining digital and chemical-analytical technologies; improved quality and environmental compliance.	Digital platform for Farmer coalitions; synergistic human-robot environment to improve farmer livelihood/resource efficiency/crop yield.
<i>Challenges</i>	End-to-end visibility and sensitivity of information; lack of agreed ontological infrastructure	Product-technology complexity (e.g., biomarkers); variability in business practices	Farmer coalitions' role in technology accessibility; farmers' skills upgrade; local water pricing policies

Often, the extant literature implicitly assumes that ‘more is better’. In partial disagreement with this view, the DTSC attributes identified in Table 1 were articulated in terms of scope and boundaries: concepts that are almost absent when discussing the extent of analytical capabilities and infrastructure required. DTSC conceptualisations are undistinguishable from that of an asset-centric DT insofar as the emphasis is placed on the generic need to merge sensor data into ‘virtual’ simulation models (e.g., Ghobakhloo, 2018). Figure 2 summarises pictorially a possible relationship between DT and DTSC. It emphasises the role of supply chain ontologies as digital backbones, and the intended use of the infrastructure being interrogated, suggesting that currently available SCND tools capabilities may suffice for ‘one off’ strategic deployment, which is common in business practice.



**Figure 2.** Schematic relationship between Digital Twin Supply Chain and asset-centric Digital Twin concepts.

## 5. Closing remarks

This paper contributes to the debate on DTSC by providing a critical reading of the extant literature from a supply chain and operations management perspective. It derives possible attributes of a DTSC from exploratory industry cases centred on new capabilities provided by advanced manufacturing technologies and industrial digitalisation. Opportunities and challenges associated with each case are discussed, within and beyond those strictly associated with specific technology interventions. Overall, the conceptualisation of DTSC in prior literature is inchoate; the likely benefits associated to it are uncertain or ill-defined; and its concrete applications sparse. Perhaps unsurprisingly, the opposite view is held by major vendors of software tools. In this paper, we begin the task of defining the key attributes of a DTSC which will inform future work on its potential, and how it might go beyond established visualisation and computational capabilities offered by existing SCND and simulation platforms.

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## References

Alam, K.M., El Saddik, A., 2017. C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems. *IEEE Access*, Vol. 5, pp. 2050–2062.

- Badman, C., Srari, J.S., 2018. *ReMediES: Collaborative research in action*. Institute for Manufacturing, University of Cambridge. Available at: <<https://remediesproject.com/>>.
- Bao, J., Guo, D., Li, J., Zhang, J., 2019. The modelling and operations for the digital twin in the context of manufacturing. *Enterprise Information Systems*, Vol. 13, No. 4, pp. 534–556.
- Batty, M., 2018. Digital twins. *Environment and Planning B: Urban Analytics and City Science*, Vol. 45, No. 5, pp. 817–820.
- Calatayud, A., Mangan, J., Martin, C., 2019. The self-thinking supply chain. *Supply Chain Management*, Vol. 24, No. 1, pp. 22–38.
- Caruso, L., 2018. Digital innovation and the fourth industrial revolution: epochal social changes?. *AI & Society*, Vol. 33, No. 3, pp. 379–392.
- Cheng, Y., Zhang, Y., Ji, P., Xu, W., Zhou, Z., Tao, F., 2018. Cyber-physical integration for moving digital factories forward towards smart manufacturing: a survey. *International Journal of Advanced Manufacturing Technology*, Vol. 97, No. 1, pp. 1209–1221.
- CMAC, 2018. *Future Continuous manufacturing and Advanced Crystallisation Manufacturing Research Hub - Annual Review 2018*. Available at: <[cmac.ac.uk](http://cmac.ac.uk)>.
- Cortada, J.W., 2011. *Information and the modern corporation*. MIT Press, Cambridge, MA.
- Defraeye, T., Tagliavini, G., Wu, W., Prawiranto, K., Schudel, S., Assefa Kerisima, M., Verboven, P., Bühlmann, A., 2019. Digital twins’ probe into food cooling and biochemical quality changes for reducing losses in refrigerated supply chains. *Resources, Conservation and Recycling*, Vol. 149, pp. 778–794.
- Ghobakhloo, M., 2018. The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *Journal of Manufacturing Technology Management*, Vol. 29, No. 6, pp. 910–936.
- Grieves, M., Vickers, J., 2017. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems, in Kahlen, F.-J., Flumerfelt, S. and Alves, A. (Eds.), *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, Springer, Cham, pp. 85–113.
- HM Treasury, 2018. *BUDGET 2018*, London.
- Ivanov, D., Dolgui, A., Das, A., Sokolov, B.V., 2018. Digital Supply Chain Twins: Managing the Ripple Effect, Resilience, and Disruption Risks by Data-Driven Optimization, Simulation, and Visibility, in Ivanov, D., Dolgui, A. and Sokolov, B. (Eds.), *Handbook of Ripple Effects in the Supply Chain*. Springer.
- Liang, W., Cao, J., Fan, Y., Zhu, K., Dai, Q., 2015. Modeling and implementation of cattle/beef supply chain traceability using a distributed RFID-based framework in China. *PloS One*, Vol. 10, No. 10, e0139558.
- Liotine, M., 2020. Unlocking digital innovation: guiding principles for driving digital technology in the supply chain, in Pagano, A.M. and Liotine, M. (Eds.), *Technology in Supply Chain Management and Logistics*, Elsevier, Amsterdam, pp. 143–167.
- Made Smarter Review, 2017. Available at: <[www.gov.uk/government/publications/made-smarter-review](http://www.gov.uk/government/publications/made-smarter-review)>.
- Mandolla, C., Petruzzelli, A.M., Percoco, G., Urbinati, A., 2019. Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis of the aircraft industry. *Computers in Industry*, Vol. 109, pp. 134–152.
- Osorio, M.T., Moloney, A.P., Brennan, L., Monahan, F.J., 2012. Authentication of beef production systems using a metabolomic-based approach. *Animal*, Vol. 6, No. 1, pp. 167–172
- Park, K.T., Nam, Y.W., Lee, H.S., Im, S.J., Noh, S.D., Son, J.Y., Kim, H., 2019. Design and implementation of a digital twin application for a connected micro smart factory. *International Journal of Computer Integrated Manufacturing*, Vol. 32, No. 6, pp. 596–614.
- Ricke, S.C., Van Loo, Ellen J., Johnson, M.G., O’Byrne, C.A. (Eds.), 2012. *Organic meat production and processing*, IFT Press; Ames (Iowa).
- Saudagar, M., Ye, M., Al-Otaibi, S., Al-Jarba, K., 2019. Smart manufacturing: Hope or hype?. *Chemical Engineering Progress*, Vol. 115, No. 6, pp. 43–48.
- Srari, J.S., Settanni, E., and Aulakh, P.K. (in press). Evaluating the Business Case for Continuous Manufacturing of Pharmaceuticals: A Supply Network Perspective, in Nagy Z.K., El Hagrasy, A., Lister, J. (Eds): *Continuous Pharmaceutical Processing*. Springer.
- Stadtler, H., Kilger, C., Meyr, H. (Eds.), 2015. *Supply chain management and advanced planning: Concepts, models, software and case studies*. 5th ed. Springer, Heidelberg.
- Tao, F., Zhang, H., Liu, A., Nee, A.Y.C, 2019. Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics*, Vol. 15, No. 4, pp. 2405–2415.
- Trokanas, N., Srari, J.S., 2017. Towards an ontological backbone for pharmaceutical digital supply chains, in Espuña, A., Graells, M. and Puigjaner, L. (Eds.), *Proceedings of the 27th European Symposium on Computer Aided Process Engineering (ESCAPE)*, Elsevier.
- Tsolakis, N., Bechtsis, D., Srari, J.S., 2019. Intelligent autonomous vehicles in digital supply chains. *Business Process Management Journal*, Vol. 25, No. 3, pp. 414–437.
- World Economic Forum, 2018. *The Next Economic Growth Engine: Scaling Fourth Industrial Revolution Technologies in Production*, Cologny/Geneva.