# System-of-system Approaches and Challenges for Multi-Site Manufacturing

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***Abstract -*** *In the multi-site manufacturing domain, systems-of-systems (SoS) are rarely called so. However, there exist a number of collaborative manufacturing paradigms which closely relate to system-of-system principles. These include distributed manufacturing, dispersed network manufacturing, virtual enterprises and cloud manufacturing/manufacturing-as-a-service. This paper provides an overview of these terms and paradigms, exploring their characteristics, overlaps and differences. These manufacturing paradigms are then considered in relation to five key system-of-systems characteristics: autonomy, belonging, connectivity, diversity and emergence. Data collected from two surveys of academic and industry experts is presented and discussed, with key challenges and barriers to multi-site manufacturing SoS identified.*

**Keywords:** Integrated multi-site manufacturing, system-of-systems, SoS, collaborative manufacturing, distributed manufacturing, dispersed network manufacturing, virtual enterprise, cloud manufacturing, manufacturing-as-a-service.

## 1 Introduction

Competitive pressures mean that manufacturers need to deliver more product variants within shorter lead times, often in low and fluctuating volumes, and at lower prices. This has given rise to a number of manufacturing paradigms, including lean production, agile manufacturing, bionic manufacturing and holonic manufacturing, which attempt to improve the manufacturer's capacity to meet these shifting requirements. At the same time, there is an increasing trend towards more geographically distributed manufacturing at both the intra- and inter-firm level, brought about by costs, tax policies and specialisation on core businesses. Few vertically integrated manufacturing enterprises exist today with the vast majority of manufacturers embedded within globally distributed supply networks.

The geographic distribution of manufacturing can be seen at both the intra- and inter-firm level. Intra-firm manufacturing networks typically involve large global manufacturers in industries such as automotive, aerospace and electronics, which have multiple manufacturing sites distributed across the world. At the inter-firm level, geographically distributed manufacturing occurs as individual manufacturers self-organise and collaborate in the delivery of specific products to customers.

In parallel to manufacturing paradigms in general, a number of similar collaborative manufacturing paradigms have emerged. These include distributed manufacturing, dispersed network manufacturing, virtual enterprises and cloud manufacturing/ manufacturing-as-a-service. A common feature of these new paradigms is the temporary nature of the collaborative manufacturing effort. Manufacturers self-organise into collaborative networks in response to customers' needs, dissolving once these needs have been satisfied. This principle behaviour is highly equivalent to SoS characteristics. For this reason, the future of system-of-systems in integrated multi-site manufacturing is currently being explored in Road2SoS, an EU FP7 project. The objective of this project is the development of SoS roadmaps in 4 domains: (1) integrated multi-site manufacturing, (2) multi-modal traffic control, (3) smart grid and distributed energy generation, and (4) emergency and crisis management. This paper provides a basis for understanding the underlying characteristics of SoS in the multi-site manufacturing domain. It goes on to present and analyse data from two surveys with domain experts, identifying current challenges and potential future trends.

## 2 Multi-site manufacturing paradigms

In the production domain, systems-of-systems are rarely called so. However, there exist various terms which closely relate to system-of-system principles. This section gives an overview on the most important terms and paradigms, their characteristics, overlaps and differences.

### 2.1 Distributed manufacturing

Distributed manufacturing is "a new pattern of interfirm relationships evolving network-wide integration by creating different forms of interentity processes" [1]. It is a temporary alliance of manufacturers, suppliers and customers, which combine their knowledge and competencies in order to meet clearly defined market

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opportunities. The organisations within it are nearly autonomous as they execute their tasks. While individual operations can either be coordinated through a central organisation or decentralised, there is a need for some form of coordination and synchronisation through information exchange [2]. Drivers of distributed manufacturing include the availability of reconfigurable manufacturing systems, technologies for decision-making support, enhanced human-machine interfaces, and collaboration software [1].

### 2.2 Dispersed network manufacturing

The concept of dispersed network manufacturing originates in industrial networks theory and is defined as "an organisational manifestation for collaboration between and coordination across loosely connected agents" [3]. These agents are typically small and medium sized enterprises (SMEs), which are geographically distributed, often on a regional scale rather than a global one. Their objective is to pool their capabilities in order to provide the necessary production capacity that a larger customer requires [4]. To meet this objective, the membership of the network may change over time. The degree of autonomy possessed by each member within the network varies and the interactions between members lead to the emergence of collective behaviours that go beyond the control of any single firm [5].

Related to dispersed network manufacturing is the concept of a 'dispersed manufacturing network', the "particular combination of SMEs that has formed in accordance with the principles of DNM [dispersed network manufacturing]" [4]. In this topology, SMEs form dynamic networks in order to satisfy customer demand, dissolving following the satisfaction of those demands. While there is no fixed membership or ownership of the network in both dispersed network manufacturing and dispersed manufacturing networks, a key difference lies in the strength of relationships between network members. In dispersed manufacturing networks, these relationships are much more significant and maintaining the relationship is a key enabler for this concept [4].

### 2.3 Virtual enterprises and organisations

A virtual enterprise is "a temporary alliance of enterprises that come together to share skills or core competencies and resources in order to better respond to business opportunities" [6]. It is created when organisations from a production network collaborate to form a supply chain for a single order and thereafter appear to the end customer as a single organisation. Following the fulfilment of this order, the virtual enterprise is dissolved. For the next customer order, collaboration can be continued through the original virtual organization or a different virtual organization may be established in the production network.

A related concept is the virtual organisation. The distinction between a virtual enterprise and a virtual organisation is that the former involves only profit seeking enterprises within its member, while the latter includes both for profit and not for profit organisations (e.g. universities, government agencies, charities). Three types of virtual organisations can be identified. The first type is a short-term virtual enterprise that delivers highly specialised, customised products through non-hierarchical control. The second type is the consortium virtual enterprise, in which semi-standardised products are made, with the partnership of a medium to long-term horizon. The control structure is non-hierarchical and co-operative. The final type of virtual organisation is an extended enterprise, in which a dominant enterprise uses hierarchical control to coordinate some or all of its suppliers. The extended enterprise typically delivers standardised products, with the collaboration of a long-term nature [7].

### 2.4 Cloud Manufacturing / Manufacturing-as-a-Service

Cloud manufacturing is an attempt to transfer key characteristics such as scalability (flexible increase or decrease of capacity and/or capability), location transparency (the user has not to care about resources), or costs depending on really occurred usage from cloud computing to the manufacturing domain. As a result, according to cloud-computing principles like Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS) or Software-as-a-Service (SaaS) provided by computing clouds, Manufacturing-as-a-Service (MaaS) is thought to provide the ability to manage production networks by means of service orchestration and execution. Cloud manufacturing is very closely related to the term grid manufacturing. It has more or less occurred simultaneously with the transition from grid to cloud computing in the IT domain.

## 3 Why is multi-site manufacturing a type of system-of-systems?

In considering what constitutes a system-of-systems, Sauser and Boardman define five characteristics: autonomy, belonging, connectivity, diversity and emergence [8]. Examining the new manufacturing paradigms indicates that forms of each can be considered as systems-of-systems.

### 3.1 Autonomy

An autonomous system is "situated within and a part of an environment that senses its local environment and acts upon that environment in pursuit of its own agenda" [9]. Each of the firms in the collaborative manufacturing networks pursues its own agenda. When these networks are solely SMEs, they are both managerially and operationally autonomous. However, when the networks involve subsidiaries of larger firms, the entities are only partially autonomous.

### 3.2 Belonging

Constituent systems within an SoS choose to be part of the larger system because of their needs, beliefs or fulfilment [10]. The collaborative nature of the inter-firm manufacturing networks is a defining characteristic. Firms enter the network of their own accord and set the terms of their involvement upon entering.

### 3.3 Connectivity

System-of-systems feature interoperability and a communication capability between the constituents of the SoS so that social functionality is enabled [11]. This interoperability is essential for operations in integrated multi-site manufacturing. Firms use ICT to transmit and share information across the network, distributing the total production load.

### 3.4 Diversity

Another attribute of system-of-systems is that they feature visible heterogeneity. That is, they include “distinct or unlike elements or qualities in a group” [8]. Whether inter-firm or intra-firm, each of the collaborative manufacturing networks is an amalgam of such heterogeneous entities. Each firm has distinctive capabilities and competencies and participates in the network so that it can obtain access to those complementary capabilities and competencies that it does not possess.

### 3.5 Emergence

The final core concept in Sauser and Boardman’s model is that system-of-systems exhibit emergent attributes, including unexpected structures and behaviours [8]. The multi-site manufacturing network paradigms described in this paper are each expected to be transitory in nature as they dissolve following the delivery of the customer’s requirements. However, there is the potential for collaborations to endure and to take on new forms beyond the completion of the initial network’s objectives.

## 4 Challenges and future trends

It is apparent that manufacturing across multiple sites is no longer determined solely by the supply network but has begun to operate in collaborative networks that possess system-of-systems attributes. In an attempt to understand how integrated multi-site manufacturing is evolving and developing system-of-system characteristics, two surveys have been conducted at a European level as part of the Road2SoS project. These surveys sought the views of experts in the field, bringing together perspectives from industry and academia.

The aim of the first survey was to capture perspectives on the future direction of technological developments in multi-site manufacturing. The survey was conducted with 17 experts in the multi-site manufacturing domain. 10 surveys were completed through interview, with the other 7 conducted through an online questionnaire.

The objective of the second survey was to capture insights into the market factors that are enabling or inhibiting the adoption of multi-site manufacturing. The survey was conducted as an online questionnaire and was completed by 19 industrial experts in multi-site manufacturing.

### 4.1 SoS concepts in multi-site manufacturing

Respondents to the first survey provided a wide range of definitions as to what constitutes a system-of-systems in multi-site manufacturing. Example definitions included:

- A complex system which is initiated by integrating autonomous systems by means of interfaces and infrastructure in order to reach a common goal.
- Multi-site production running autonomous production sites. Each site is focusing on specific markets strategically and to gain competitive advantage these sites are controlled centrally.
- The application of ICT to the distributed business processes linking diverse manufacturing enterprises in supply chains, value networks and business ecosystems.
- A system-of-systems consists out of heterogeneous components which can work in their specific domain independently but can be orchestrated working together in a way to have a larger system.

This data indicates that there remains no clear definitional consensus of SoS in multi-site manufacturing among academics and practitioners who work in the area. The novelty of the SoS field is also highlighted by respondents (Figure 1), as the maturity of SoS architectures and tools lags well behind that of SoS concepts.

While over half the respondents believe that SoS concepts are mature or well advanced, around 70% of respondents believed that SoS architectures and SoS tools are only elementarily developed or underdeveloped. Overall, two-thirds of respondents considered the multi-site manufacturing SoS to be elementarily developed.

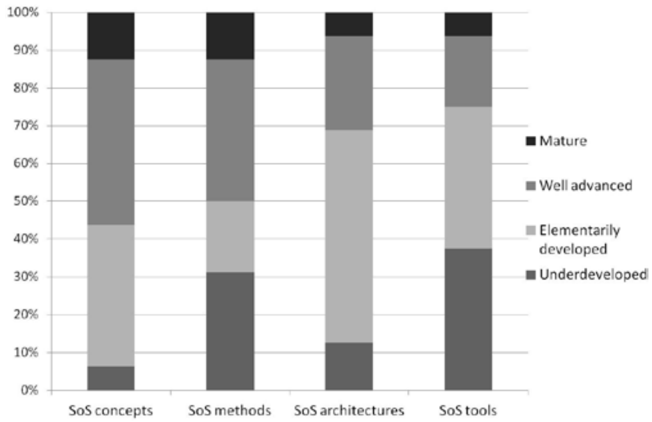


Figure 1. The maturity of SoS concepts, methods, architectures and tools in multi-site manufacturing *(Survey 1, n=16)*

There are also a variety of terms used to describe complex systems, systems-of-systems and collaborative networks. Figure 2 shows the responses to the concepts and principles of SoS relevant to multi-site manufacturing. The most relevant concepts and principles are shown on the left of the figure, with the six most relevant judged to be: (1) flexibility, (2) adaptability, (3) autonomy of the subsystems, (4) network, (5) modularity, and (6) evolutionary.

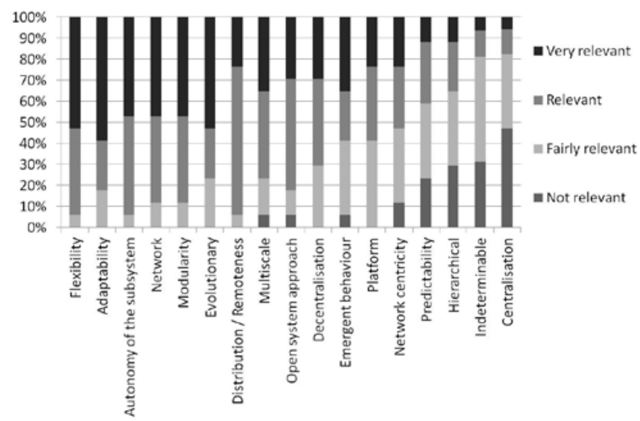


Figure 2. Main principles and concepts in multi-site manufacturing SoS *(Survey 1, n=17)*

## 4.2 Drivers of multi-site manufacturing SoS

The drivers for the adoption of SoS approaches in multi-site manufacturing are numerous. Table 1 summarises the survey responses collected on this topic, which were scored on a five-point Likert scale. Each of the drivers described are contribute to improving the firm's competitiveness. The most highly rated are concerned with how SoS approaches can help improve the firm's ability to respond to customer demands while improving manufacturing efficiency and reducing costs.

Table 1. Domain drivers in multi-site manufacturing SoS *(Survey 2, n=18)*

| Domain driver | Mean |
|---|---|
| Reduction of inventories and lead times | 4.44 |
| Increased responsiveness to customer demands | 4.39 |
| More economical use of resources, cost reduction | 4.33 |
| Maximized manufacturing efficiency | 4.28 |
| Increased flexibility | 4.28 |
| Increased ability for on-demand production | 4.06 |
| Reduced equipment integration and production ramp-up times | 3.94 |
| Enabling product and/or process innovations | 3.89 |
| Consistent/integrated product tracking and tracing | 3.83 |
| Reduced need for maintenance | 3.82 |
| Better control of process parameters | 3.78 |
| Integrated, continuous scheduling | 3.72 |
| Product customization | 3.61 |
| Reduction of environmental impact | 3.61 |
| Increased scalability | 3.59 |
| Condition monitoring | 3.35 |
| More diversified production | 3.22 |
| Decreased dependency on strong players in the market | 3.22 |
| Increased degree of automation | 3.17 |
| Greater number of product variants | 3.17 |

## 4.3 Challenges of multi-site manufacturing SoS

Survey respondents provided insights into the key challenges for the implementation of system-of-systems in integrated multi-site manufacturing in the next five years. These challenges include the following:

- Reference implementations and SoS showcases to increase acceptance
- Development of (quasi) standards for integration of systems and description of systems functionality
- Understand how to link production with the broader value chain
- Data capture and interpretation
- Being able to access the information (avoid human information overload), and improve visualisation
- Predictive software
- Understanding how to create resilience and adaptability to change
- Resolve legal issues (also supported by implementation of the systems)
- Skills shortages

Focusing on the ICT and technological challenges, survey respondents highlighted the importance of interoperability. As Figure 3 illustrates, the seamless integration of systems and components, between both new and legacy systems, in multi-organisation networks are key technical challenges that need to be overcome for SoS practices to be more widely adopted.

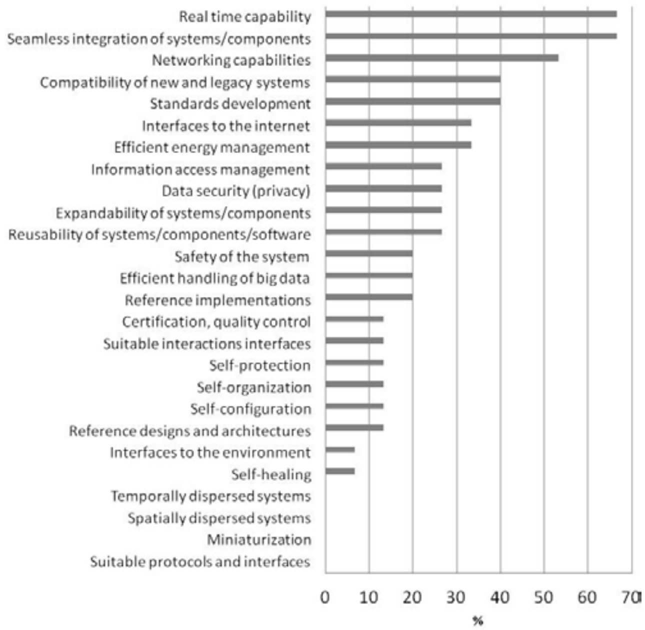


Figure 3. Technology and ICT challenges in multi-site manufacturing SoS *(Survey 2, n=17)*

To overcome these challenges, survey respondents identified a number of technologies that would impact the future development of system-of-systems in multi-site manufacturing. The most identified technologies were the following:

- Cloud computing
- Communications standards for information exchange (e.g. SAP)
- Manufacturing service descriptions
- Plug-and-produce seamless reconfigurable production environments
- Product tracking throughout the supply chain
- Integration of design tools in order to specify/customise product parameters throughout the whole supply chain
- Order management software in non-hierarchical networks

## 4.4 Barriers to multi-site manufacturing SoS

Respondents also identified a number of key socio-economic barriers to the implementation of systems-of-systems in multi-site manufacturing. These barriers include the following:

- Distribution of knowledge about SoS in industry
- Short term focus, e.g. efficiency-only focus
- Economic viability and liability
- Political interests, power, and incentive structures
- Economic interdependencies
- Protection of intellectual property
- World trade barriers
- Uncertainty in global macro-economic trends
- Migration of production to low cost countries
- Lack of finance to enable the implementation of IT infrastructure in emerging economies

Focusing on the social, economic, political and legal barriers to the implementation of SoS in multi-site manufacturing highlighted that these barriers are as significant as the technical challenges. Table 2 summarises the survey responses collected on this topic, which were scored on a five-point Likert scale. The most highly rated barriers concern how organisations work together and finding ways to capture economic value from SoS approaches.

Table 2. Barriers to implementing SoS in multi-site manufacturing *(Survey 2, n=15)*

| Issue | Mean |
|---|---|
| Problems related to multiple ownership | 4.27 |
| Lack of availability of skilled personnel | 4.00 |
| Intellectual property issues | 4.00 |
| Lack of appropriate business models | 3.93 |
| Concerns about security and privacy | 3.87 |
| High initial investment | 3.87 |
| Lingual and cultural differences in global networks | 3.80 |
| Antitrust policies hindering cooperation of companies establishing System of Systems implementations | 3.80 |
| Risk-benefit ratio unclear | 3.67 |
| Time to market too long or unclear | 3.64 |
| Absence of demonstration / technology and approach insufficiently tested | 3.50 |
| Uncertain demand | 3.47 |
| Lack of organizational acceptance | 3.40 |
| Concerns about system stability and failures | 3.40 |
| Software licensing | 3.38 |
| Concerns about false information conveyed by the system | 3.27 |
| Individual action is highly risk fraught | 3.23 |
| Regulatory issues | 3.07 |
| Certification | 3.00 |
| General preference for centralized, hierarchical systems | 2.93 |
| Lack of public acceptance | 2.80 |
| Lack of public funding | 2.73 |

# 5 Conclusions

This paper has focused on the emergence of SoS approaches in the domain of integrated multi-site manufacturing. It is apparent that SoS are becoming more widespread given the technological advances that have been made in ICT and the potential for greater responsiveness to customer demand. However, significant technical challenges and socio-economic barriers remain.

The Road2SoS project aims to build of these survey insights. Future work will bring together expert practitioners at a roadmapping workshop. The survey data will be synthesised with desk research to create a pre-populated roadmapping template. This preliminary roadmap will be used at the workshop, with participants working together to develop a clearer vision of the future challenges, enablers and barriers that remain in multi-site manufacturing SoS. Possible future applications scenarios for the domain in the next 15 years will be explored and specific actions for the materialisation will be developed. It is expected that this work will shape the EU's Horizon 2020 research and funding landscape.

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# References

[1] H. Kühnle, “Distributed Manufacturing: Paradigm, Concepts, Solutions and Examples,” in *Distributed Manufacturing: Paradigm, Concepts, Solutions and Examples*, H. Kühnle, Ed. London: Springer-Verlag, 2010, pp. 1-9.

[2] T. Sauter and A. Treytl, “Communication Systems as an Integral Part of Distributed Automation Systems,” in *Distributed Manufacturing: Paradigm, Concepts, Solutions and Examples*, H. Kühnle, Ed. London: Springer-Verlag, 2010, pp. 93-111.

[3] R. Dekkers, “Introduction,” in *Dispersed Manufacturing Networks: Challenges for Research and Practice*, R. Dekkers, Ed. London: Springer-Verlag, 2009, pp. 3-12.

[4] H. Noori and W. B. Lee, “Dispersed Network Manufacturing: An Emerging Form of Collaboration Networks,” in *Dispersed Manufacturing Networks: Challenges for Research and Practice*, R. Dekkers, Ed. London: Springer-Verlag, 2009, pp. 39-58.

[5] H. Kühnle, “Self-Similarity and Criticality in Dispersed Manufacturing: A Contribution to Production Networks Control,” in *Dispersed Manufacturing Networks: Challenges for Research and Practice*, R. Dekkers, Ed. London: Springer-Verlag, 2009, pp. 59-76.

[6] L. M. Camarinha-Matos and H. Afsarmanesh, “Collaborative networks: a new scientific discipline,” *Journal of Intelligent Manufacturing*, vol. 16, no. 4-5, pp. 439-452, 2005.

[7] M. T. Martinez, P. Fouletier, K. H. Park, and J. Favrel, “Virtual enterprise – organisation, evolution and control,” *International Journal of Production Economics*, vol. 74, no. 1-3, pp. 225-238, 2001.

[8] B. Sauser and J. Boardman, “Taking Hold of System of Systems Management,” *Engineering Management Journal*, vol. 20, no. 4, pp. 3-9, 2008.

[9] R. K. Garrett, S. Anderson, N. T. Baron and J. D. Moreland, “Managing the Interstitials , a System of Systems Framework Suited for the Ballistic Missile Defense System,” *Systems Engineering*, vol. 14, no. 1, pp. 87-109, 2010.

[10] A. Gorod, B. Sauser, and J. Boardman, “System-of-Systems Engineering Management : A Review of Modern History and a Path Forward,” *IEEE Systems Journal*, vol. 2, no. 4, pp. 484-499, 2008.

[11] M. J. Dimario, J. T. Boardman, and B. J. Sauser, “System of Systems Collaborative Formation,” *IEEE Systems Journal*, vol. 3, no. 3, pp. 360-368, 2009.