Higher-Level Capabilities of System-of-Systems Constituents: A Case of Industrial Ecosystems

Jakob Axelsson
Mälardalen University & RISE Research Institutes of Sweden
Västerås, Sweden
jakob.axelsson@mdu.se

Peter Eriksson
Blue Institute
Västerås, Sweden
peter.eriksson@blueinst.com

***Abstract*—In a system-of-systems, independent constituent systems collaborate to achieve broader capabilities they cannot provide on their own. This paper investigates the nature of the constituent system capabilities beyond basic operational actions, to achieve a deeper understanding of what is required to participate in a system-of-systems. Through a case study of industrial ecosystems, the need is shown for planning how to use basic operational capabilities, for dynamic capabilities to achieve long-term evolution, and for resilience capabilities to deal with perturbations. This also affects the governance of the system. The findings are used to extend an existing conceptual model of constituent systems and to characterize collaboration in a system-of-systems that implements a value network.**

Keywords—systems-of-systems, constituent systems, capability models, production planning, industrial ecosystem, value network.

I. Introduction

A *system-of-systems (SoS)* is commonly defined as a set of systems that interact to provide a unique capability that none of the *constituent systems (CS)* can accomplish on its own [1]. A CS of an SoS is primarily characterized by having *operational and managerial independence* [2]. It can thus be meaningfully used on its own outside the SoS, and it can decide for itself when and how to participate in an SoS.

SoS have previously been studied in application areas such as defense, aerospace, transportation, energy, and disaster management [3]. However, the definition of an SoS also fits very well with the characteristics of an industrial business ecosystem, such as a supply chain or value network, although this connection has not been studied extensively before. In the industrial ecosystem context, the CS would be the individual firms involved. These are independent in their decisions on how to collaborate, yet dependent on their suppliers and customers once a collaboration has been established.

The industry is going through rapid digitalization, which automates many flows of information not only within but also between companies. This increases the socio-technical nature of firms, but it is a perspective with which the industry struggles. By leveraging conceptual ideas from SoS engineering (SoSE) on how to model capabilities, better support for deciding how to increase the firm's capability through digitalization can be found. Our ambition is thus to provide better analysis models that focus on value creation in the SoS, which can serve as a foundation for improvements in collaboration. On the other hand, by studying industrial ecosystems as SoS, we can also learn more about the characteristics of highly complex and socio-technical CS. That knowledge can be useful in other SoS settings as well.

This paper aims at contributing to both SoS research, by evolving models used for analyzing CS, and to the industry by providing better support for value network analysis and capability enhancement in the light of digitalization. As a theoretical framework, it uses an existing conceptual model of CS that focuses on operational capabilities and the nature of CS independence [4]. The framework is generic and only gives details about a few specific capabilities.

This research was funded by Vinnova (Sweden's innovation agency), grant no. 2021-02499 and the Knowledge Foundation, grant no. 20200230.

Through a case study, we extend this framework by identifying certain higher-level capabilities that are important in planning the use of capabilities, the evolution of the CS, and dealing with perturbations. The case study investigates several firms in different process and manufacturing industries. It focuses on internal production planning, which is a central capability both to coordinate internal activities and in interacting with partners in the business ecosystem.

The main result of the paper is the derivation of a refined conceptual model of CS, that also includes higher-level capabilities. This model can both be used to improve practical SoS and as a basis for continuing research on SoSE methods.

The remainder of this paper is structured as follows: In the next section, some related work is reviewed. In Section III, the theoretical framework for modeling CS capabilities and independence is introduced. In Section IV, the case study is presented, followed in Section V by an account of the findings. In Section VI, the identified characteristics of a CS are put into the context of SoS and value networks, and in the final section, the conclusions are summarized together with some indications of how this research will continue.

II. Related Work

In this section, some related research will be reviewed, starting with a background on value networks, which can be seen as a business model of an SoS. Then, capabilities in the context of organizations are discussed, and finally, the application to industrial production planning is summarized.

A. Value Networks

The value chain model [5] is commonly used for analyzing a firm's relations with other firms. However, this model suffers from its linear nature, where the firm is a transformer of input material from suppliers to finished products delivered to customers. This view has some value in manufacturing but is less valid in other industries. Digitalization also moves industry further away from this model, by introducing large-scale bidirectional dataflows, and on-demand production.

Stabell and Fjeldstad [6] identified two alternatives to value chains, called value shops and value networks. In the value shop, the customer is co-creating the value, and the firm is providing services. In a value network, the firm's focus is on mediating the relations between different customers. An example in an SoS context of such a mediated value network was provided in a case study on truck platooning [7].

Christensen [8] studied value networks in the context of disruptive innovation and claimed that it is very difficult for a new entrant to affect the structure of a network. Innovations instead often consist of finding new types of relations.

Normann and Ramirez [9] focus on the dynamic nature of value networks and discuss the idea of constellations as temporary structures that emerge for some time. This idea of constellations is similar to how it has been used in SoSE [10].

Allee [11] provides a method for the analysis of value networks, with a focus on roles and deliverables. She also introduces the concept of value conversion, which means that an intangible value can be converted into a tangible one.

The important aspect that business ecosystems and SoS may overlap and collide is discussed shallowly in [12].

B. *Capabilities in Business and Organization Theory*

The concept of capability is widely used in work on SoS, primarily with defense applications [13]. However, the term is also often used in the business sector, such as in Enterprise Architecture (EA), which supports the business with IT systems. A popular concept in EA is capability maps [14] which structure the capabilities of an organization in layers.

From organizational theory, an influential concept is that of dynamic capabilities [15] which allow an organization to adapt to new circumstances. This is similar to ideas described in second-order cybernetics [16].

C. *SoS in Industrial Production Ecosystems and Planning*

An early attempt at applying SoSE to manufacturing was provided in [17]. It focuses on a Lean-inspired method for designing the architecture of a firm as an SoS. Another approach uses system dynamic models to evaluate textile industry production as an SoS [18]. It covers aspects related to work in progress and external perturbations and suggests improvements based on Lean.

In [19], production planning with a focus on sustainability is investigated through the lens of SoS. Another SoS-based approach, focusing on interoperability in manufacturing tasks and resource planning, is given in [20]. An agent-based model is used for the evaluation of orchestration mechanisms.

Automation is an important aspect of industrial production, and this is discussed in terms of collaborative SoS in [21]. Several key concepts and challenges are identified.

III. Theoretical Framework

This paper will use a previously proposed model of CS capabilities as a theoretical framework [4]. The framework consists of a deeper characterization of the capability concept, and a model of an agent that explains how it uses a combination of key capabilities to achieve its independence. This section summarizes the framework for those two aspects.

A. *Capability Concept*

The intuitive definition of *capability* is ”something a system could do” (see e.g. [22]). Doing something is interpreted as purposefully changing the state of some part of the world, and a capability is therefore seen as a *state-transforming process*. This means that the capability can be activated from a certain set of world states, and it will, after some time, result in a state which meets certain conditions. This is usually a complex process, involving the planning and execution of many steps and the coordination of several actors, not just a simple function from one state to the next (see [23]).

Capabilities typically require access to some *resources*, which are either consumed as part of the transformation or reserved during the transformation but then available for other use. Resources can be tangible or intangible, thus both material and information can be used by a capability.

A certain capability can often be carried out in several different ways. This can affect the duration of the capability or the kind and amount of resources consumed. When an agent chooses to activate a capability, it thus also needs to decide how to use it by setting certain parameters.

A CS typically has several different capabilities, and the choice of how to use them needs to take into account any dependencies they may have. For example, several capabilities may require the same resources or affect the same parts of the world state, which would then require prioritization or scheduling of the capability activations.

B. *Constituent System Independence*

The notion of CS independence [2] can be interpreted as the CS having a choice of if and how it will put its capabilities to the service of the SoS, or whether to use them for its own purposes. To make those decisions, additional mechanisms are needed in the agent, as illustrated in Fig. 1.

The agent needs a *perception* capability to allow it to gather information about the state of the surrounding world. The perception allows it to collect and maintain a *world model*, which stores its understanding of the state of the world at a certain abstraction level, as well as abstract notions about the mechanics of the world, which enables it to predict how the world could evolve. This provides a situation awareness which is important input both to *decision making* and planning, but also to the operational capabilities.

Usually, the agent has many alternatives for how to use its capabilities in a given situation, and choices have to be made. It will strive to maximize utility (according to how it values certain outcomes), and therefore an *expected utility function* is needed to determine the incentives for different choices.

IV. Case Study

To investigate the nature of the firm as a CS in the SoS representing an industrial business ecosystem, we conducted a case study. In this section, the study objective, method, and selected cases are presented.

A. *Objective*

Following the terminology of [24], this was an exploratory case study, where the aim was to identify a broad range of capabilities that a firm needs to have to support its interaction with other CS. The ambition was not to study a particular firm in detail to explain how it works, nor was it to provide an exhaustive list of capabilities relevant to all firms, but to get a range of examples that a model should be able to cover.

B. *Method*

With this objective in mind, we designed the study as a multi-case, where data from several firms in different process and manufacturing industries were included.

1) Unit of analysis: The unit of analysis was primarily the production planning organization within each of the firms. This part of the organization was chosen based on the assumption that it plays a key role in the firm. It needs to consider both external customer relations (incoming orders) and suppliers (availability of material), as well as internal

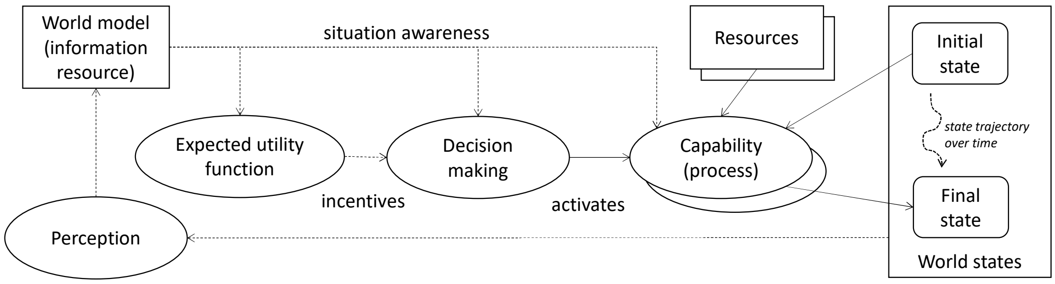

Fig. 1. Elements of a decision-making agent representing a CS (based on [4]).

entities such as the production process and management. The assumption that production planning is key is also theoretically supported by the framework since planning can be seen as an element of decision-making in Fig. 1.

2) Data collection: Data was collected through interviews with production planners at the selected firms, or with other researchers who had already gathered a deep understanding of a firm through prior collaboration. A set of questions for the interviews were deduced from the framework in Section III, to ensure that no essential aspects were missed. These questions served more as a checklist for things to cover, whereas the actual interviews followed an open flow, and included many other topics to capture as much potentially relevant information as possible.

The interviews were carried out by the two authors together, both taking notes to reduce the risk of missing vital information. The interviews were complemented with data from public sources, such as annual reports, news, or web pages, primarily to gather context information about the firms.

3) Data analysis: The analysis consisted of structuring the notes from the interviews and trying to map them to the concepts of the theoretical framework. The analysis led to the identification of some aspects where the generic framework concepts could benefit from being refined into more concrete capability types.

C. Cases

The study included four different firms:

1) Sheet metal. Milling of sheet metal to appropriate dimensions for use in various manufacturing applications.

2) District heating. Production of heat and electricity in a thermal power station burning primarily waste products, and supplying heat to several mid-size urban areas.

3) Power grid subsystems. Manufacturing of electrical subsystems for use in power grids.

4) Nuclear fuel. Production of fuel rods for power plants.

These cases were to some extent selected based on the convenience of accessing the firms for interviews, but also to get a broad range of inputs to the research. In the next section, the findings of the case study will be presented and analyzed.

V. Results

This study aimed to gain a richer understanding of the various kinds of capabilities needed in a highly complex CS of an SoS. Through the explorative case study on industrial production systems, where the firms represent the CS in a value network SoS, it became clear that there is a need to refine the very generic decision-making capability of CS (see Fig. 1) into a set of higher-level capabilities. In this section, we will discuss the nature of those capabilities, and show how they can be organized in a refined CS capability model.

A. Mapping of Case Studies to Theoretical Framework

As a first step of the analysis, industrial production and planning were interpreted in terms of the theoretical framework in Section III. The elements of the industrial production planning were mapped to the concepts as follows:

- *Capability*: The production process that transforms material and information from one state to another. This also includes the setup of equipment for a job.
- *Resources*: The equipment, people, material, and information needed to carry out the production. This also includes if there are stocks of material.
- *Initial state*: A prerequisite that the necessary resources are available to carry out a specific production job. This includes the triggering condition, which could be a customer order for on-demand production or a forecast for speculative production.
- *Final state*: The desired outcome of the production job, given the customer orders. It includes material and information elements, considering quality factors.
- *Perception*: Relevant information includes the current state of different resources, as well as information about other actors, such as customers and suppliers.
- *World model*: Relevant information for production planning includes the current state of material stocks and their quality, the state of production equipment including expected unavailability due to maintenance, staff availability, and customer orders. Also, forecasts of these factors are used based on the organization's understanding of how they vary over time.
- *Expected utility function*: The production plan is selected to maximize the balance between income generated from the production jobs and the cost of doing so in terms of consumed resources.
- *Decision making*: The creation of the production plan can be seen as deciding how to invoke the production capability at different points in time. This includes the choice of batch sizes, whether to produce on demand or towards a product stock based on a forecast. The planning uses different kinds of resources, e.g., software tools. Important characteristics are how long the plan stretches and how often it is updated, which depends on the frequency of customer orders.

TABLE I. EXAMPLES OF CHARACTERISTICS OF THE PRODUCTION AND PLANNING CAPABILITIES IN CASE INDUSTRIES.

Characteristic (with relation to theoretical concept)	Case			
	Sheet metal	***District heating***	***Power grid subsystems***	***Nuclear fuel***
Production process (Capability)	Rolling of raw material to metal sheets	Combustion of fuel to heat water which is distributed to buildings	Assembly of electronic and mechanical components	Assembly of metal rods filled with radioactive fuel pellets
Customer orders (Initial state)	Mainly blanket agreements and call-off orders	Continuous service contracts, large number of customers	On demand orders, many individual orders each day	Few orders per year, long contracts, few customers, low degree of standardization
Stocks (Initial and final states, resources)	Limited stock of raw material	Large fuel stock, small stock of produced energy	No product stocks, a few months of components	On demand order of components
Planning (Perception, world model, expected utility function, decision making)	Mid term, frequent updates, mid size batches, mostly manual	Short term (1 day), frequent updates (hourly), based on historical demand and weather forecasts, supported by advanced software tools	Biweekly updates, mainly first in-first out	Mainly based on historical data and statistics, not on details of current state
Quality (Final state, expected utility function)	Delivery precision, material specifications	Indoor temperature at end user	Delivery precision, specification fulfilment	Extreme safety requirements on product and process

B. *Operational Production Capability Characteristics*

Production is the primary operational capability and the firm's *raison d'être*. In the studied companies, it is a highly physical process that takes incoming material and transforms it using both skilled workers and advanced equipment, into the final products that the customers desire and pay for.

Although all four cases share this general view of the production capability, they nevertheless differ on a more detailed level. Some key characteristics are summarized in Table I. These have a significant impact on the production planning needed to support efficient production.

C. *Planning the Use of Operational Capabilities*

The production capability is the firm's primary operational capability. It transforms resources into products for different customers. Making production as efficient and effective as possible in dealing with various customer demands is complicated. It requires the support of planning capabilities that determine which customer order to process at each time.

In the case study, we focused on production planning in industrial companies. This is an information-processing capability, and it can be generalized as planning for the use of operational capabilities. It is relevant for most non-trivial CS, where there is a need to optimize the use of resources or coordinate different capabilities that share resources.

A key aspect is to maximize the utilization of production resources, minimize cost and offset investments. It can be seen as a scheduling problem, that also needs to take into account the changeover time to adjust the production equipment to different product outputs. Some firms apply advanced optimization and operations research scheduling methods, whereas others use basic manual techniques and spreadsheets.

Usually, there is an ambition to standardize production processes as much as possible, since this makes it easier to control quality and efficiency, and to work with continuous improvements. It is also a prerequisite for automation to reduce costs and remove unhealthy manual work tasks. Well-described production processes also make it possible to provide standard routines for planning.

In the interviews, two aspects were recurring. The first was a frequent need to deal with unforeseen deviations. This leads to ad hoc actions outside the standardized production and planning processes, often involving an escalation to higher-level management. We regard this as a *resilience capability*.

The second issue was the fact that production staff sometimes choose to not follow the plans provided by production planning. We regard this as an opportunity for improving the production planning capability, and therefore a need for a *dynamic capability* that implements organizational learning. The resilience and dynamic capabilities are discussed in the following two subsections.

D. *Resilience Capabilities*

The resilience of a system can be seen as the capability to recover from perturbations. Those perturbations can be either internal to the system (such as unavailability of production equipment or staff, in the case of production), or external (lack of material from suppliers, or customer orders that have special demands).

Resilience can be described as "the ability to prepare and plan for, absorb, recover from or more successfully adapt to actual and potential adverse events" [25]. The disruptive triggering event creates a loss of value, and the system needs to recover from it to restore normal operation. In much of the literature, the disruptive event is dramatic and triggers a crisis management capability. However, it could also be seen as any event that falls outside the normal operations of the system, dramatic or not. In the case of production, the perturbation is thus anything that the standardized production and planning capabilities are unable to handle.

Whereas the production and planning processes strive to be standardized to achieve efficiency, a resilience capability must be as agile and flexible as possible, to respond quickly to many different events. Resource efficiency is often secondary and loss minimization and rapid recovery to normal circumstances have higher priority. This also means that this capability requires a broader world model than the primary production and must be able to correctly identify the nature of events, focus attention and decide on possible responses.

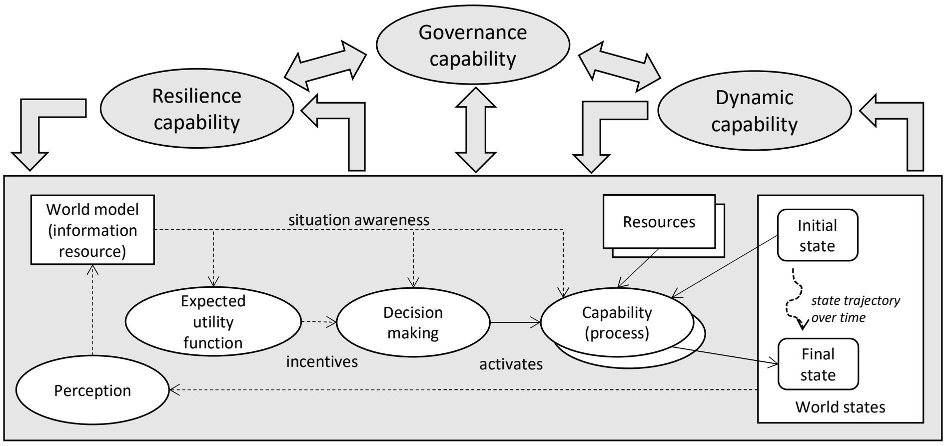

Fig. 2. Extended capability model.

Organizational resilience has been conceptualized in terms of capabilities to have three main components: anticipation, coping, and adaptation [26]. It has been shown that the nature of production has a large effect on the appropriate approaches to organizational resilience [27], particularly between discrete manufacturing vs. continuous process industry.

E. Dynamic Capabilities

In the interviews, several examples came up where there were discrepancies between the production plan and the actual production, due to decisions by the production operators.

In one case, this was probably mainly a consequence of the low update frequency of the plan. In some situations, there were rapid changes in external factors that had to be dealt with by adjusting production without waiting for a new plan.

In another case, it was likely due to unaligned priorities between planners and production staff, where the latter would divert from the plan by changing the order of jobs to increase production yield, which they had personal incentives to maximize. However, the plan had a different job order due to customer expectations on delivery time, of which the production staff was not aware. The deviation could lead to unsatisfied customers and in the end economic consequences of larger significance than increasing the yield.

The examples indicate that there is room for improvement. As was mentioned in Section II.B above, the ability of an organization to learn and improve its capabilities is often referred to as dynamic capabilities. The capabilities to improve should include not only the basic operational capabilities like production, but also improving planning, resilience, and even the dynamic capabilities themselves.

Process improvement has a long tradition in production, and the basis for this is standardized processes. Through statistical process control, tolerances can be set for production quality, and deviations from this are then easily detectable and subject to evaluation that triggers improvement activities. Similar principles have been used in the design of maturity models such as CMMI [28] for software and systems engineering. The focus is on first making the process repeatable, then defining it, as a foundation for measurements and optimization. However, it is questionable to what extent this applies to processes that by nature are less repetitive, such as resilience, and there would be room for further research on maturity models that go beyond the underlying assumptions of CMMI and the like. The higher-order capabilities are more often carried out in the form of a task force or project, rather than as a repetitive process.

F. Synthesis of Extended Capability Model

We will now summarize how the operational, planning, resilience, and dynamic capabilities interplay. This is shown in Fig. 2, which is a refinement of the previous conceptual framework from Fig. 1 and a generalization of our findings.

It is fruitful to think about the relations between these capabilities in terms of controllers. The operational capabilities are in practice almost always based on feedback control from the state of the world it is manipulating. The decision-making capability provides feedforward directives to them, in the case studies manifested in the production plans.

On top of this, the higher-level capabilities use feedback control. Resilience capabilities have a short-term focus to resolve a disruptive situation that cannot be handled by standard operating procedures. They can make use of all the resources and operational capabilities of the organization. Dynamic capabilities are long-term and result in the acquisition of additional resources or the modification of how capabilities operate. The deviations that led to the activation of resilience capabilities provide key data for the dynamic capabilities. Both these work on the entirety of the operational elements, to see not just an individual operational capability but also how it interacts with other capabilities, decision-making, and the world model. The higher-level capabilities are thus not only based on perception but also require introspection and metacognition.

Once a firm has identified the need to work systematically with preparedness for resilience and improvement through dynamic capabilities, a question becomes how much resources to spend on those, as compared to the operational capabilities. This can be seen as a governance capability that resides on yet a higher level than the others identified so far. The governance capability will rely heavily on the expected utility function and estimating where resources will be best spent given the status of the environment and internal capabilities.

VI. INTEGRATION INTO SOS AND VALUE NETWORKS

The conceptual model discussed in the previous section is intended to detail the characteristics of an independent CS, and it is interesting to see how the introduction of higher-level capabilities affects the SoS and the value network that it implements. The concepts of resilience and dynamic capabilities have relevance on that level in two ways: Firstly, a CS may address them through collaboration with other CS, relying on the capabilities of others to resolve its own resilience. Secondly, the SoS may have its own goals, that are also subject to resilience and dynamic capabilities, which can only be achieved by combining the capabilities of the CS.

The dynamic capabilities of the CS will thus lead to it seeking to adjust its position in the value network to gain benefits. As noted already in classic economic theory [29], one of the choices a firm can make regarding its evolution is whether to extend or reduce its range of capabilities. This choice depends on the ratio between the transaction costs (the costs of collaborating) and the internal costs (for providing the capability itself). As an example, a CS may repeatedly find itself in constellations with other CS to provide a joint capability, and it may then choose to expand its capabilities to be able to perform the whole task itself. This illustrates the complexity of the interactions between CS and SoS higher-level capabilities, and there is a need for SoS governance to mediate the dynamic adaptation of CS roles and incentivize CS to adapt in ways that benefit the SoS as a whole.

The kind of industries we have studied are archetypical of the classic linear supply chain model. However, the adaptations of an individual firm to both contribute to SoS capabilities and leverage collaboration to enhance its own capabilities require an intensive bidirectional flow of information. Often, the flow of material requires a feedforward or feedback information flow, but increasingly there is also a flow of information alongside the material, furthering more lifecycle details about the products. These flows can create amplifying or stabilizing loops that determine the dynamics of the value network.

VII. Conclusions and Future Work

In this paper, we have investigated the notion of capability in SoS that implement industrial value networks. We applied a previously proposed conceptual framework for operational capabilities to a case study on production planning in four different firms. This led to insights that we do not only need to consider the production and planning capabilities but also extend the model with resilience capabilities to deal with deviations and dynamic capabilities to handle organizational learning and improvement. The paper thus contributes to a broader understanding of the inner architecture of a CS, something we have previously also studied in [30]. Through the conceptual model, practitioners can get support in diagnosing the status of a particular firm to improve its collaborative capabilities in an SoS.

One direction in which this research could proceed is to study one or several firms in greater depth or to study several firms that are part of the same SoS or value network. Other directions include identifying and characterizing further higher-level capabilities. Here inspiration could be sought in how psychology has characterized human mental capabilities, or in how Beer’s Viable Systems Model [22] bases its structure on that of the human brain.

References

[1] ISO/IEC/IEEE, “Standard 21841 Systems and software engineering - Taxonomies of systems-of-systems,” ISO/IEC/IEEE, 2019.

[2] M. W. Maier, “Architecting Principles for Systems-of-Systems,” INCOSE Intl. Symp., vol. 6, no. 1, pp. 565–573, Jul. 1996.

[3] J. Axelsson, “A Systematic Mapping of the Research Literature on System-of-Systems Engineering,” in IEEE System of Systems Eng. Conf., 2015.

[4] J. Axelsson and P. Svenson, "On the Concepts of Capability and Constituent System Independence in Systems-of-Systems," 17th Annual System of Systems Engineering Conf., 2022, pp. 247-252.

[5] M. E. Porter, “Competitive Advantage: Creating and Sustaining Superior Performance,” Simon & Schuster, 1985.

[6] C. B. Stabell and Ø. D. Fjeldstad, “Configuring Value For Competitive Advantage: On Chains, Shops, and Networks,” Strategic Mgmt. J., Vol. 19, pp. 413-437, 1998.

[7] J. Axelsson, “Business Models and Roles for Mediating Services in a Truck Platooning System-of-Systems,” IEEE Systems of Systems Eng. Conf., pp. 113-118, 2019.

[8] C. Christiansen, “The Innovator’s Dilemma: When New Technologies Cause Great Firms to Fail,” Harvard Business Review Press, 1997.

[9] R. Normann and R. Ramírez, “From value chain to value constellation: Designing interactive strategy,” Harvard Business Review, Vol. 71, Issue 4, pp. 65-77, July-Aug, 1993.

[10] J. Axelsson, “A Refined Terminology on System-of-Systems Substructure and Constituent System States,” IEEE Systems of Systems Eng. Conf., pp. 31-36, 2019.

[11] V. Allee, “The Future of Knowledge: Increasing Prosperity Through Value Networks,” Butterworth-Heinemann, 2003.

[12] S. Amorim, E. Almeida, J. D. McGregor, and C. Chavez, “When Ecosystems Collide: Making Systems of Systems Work,” Proc. European Conference on Software Architecture Workshops, 2014.

[13] J. Martin, J. Axelsson, J. Carlson, and J. Suryadevara, “The Capability Concept in the Context of Systems of Systems: A Systematic Literature Review,” Proc. 8th Intl. Symp. on Systems Engineering, 2022.

[14] W. Ulrich and M. Rosen, “The business capability map: The Rosetta stone of business/IT alignment,” Enterprise Arch., vol. 14, No. 2, 2014.

[15] D. J. Teece, G. Pisano, and A. Shuen, “Dynamic capabilities and strategic management,” Strategic Mgmt. J., Vol. 18, No. 7, 1997.

[16] B. Scott, “Second order cybernetics: an historical introduction,” Kybernetes, Vol. 33, No. 9/10, pp. 1365-1378, 2004.

[17] A. Alfieri, M. Cantamessa, F. Montagna, “SoS Methodologies for the Definition of Lean Manufacturing Systems,” IFAC Proc. Vol. 42, No. 4, pp. 1014-1019, 2009.

[18] A. Mahmood, “Gazing Lean through the lens of System of Systems Dynamics: A case of weaving mill,” Journal of Engineered Fibers and Fabrics, Vol. 14, 2019.

[19] M. Zarte, A. Pechmann, and I. L. Nunes, “System-of-Systems Approach for Sustainable Production Planning and Controlling in Manufacturing Companies”, Proc. Intl. Conf. on Applied Human Factors and Ergonomics, pp. 413-421, 2019.

[20] Å. Fasth-Berglund, D. Romero, M. Åkerman, B. Hodig, and A. Pichler, “Agent- and Skill-Based Process Interoperability for Socio-Technical Production Systems-of-Systems,” Proc. IFIP Intl. Conf. on Advances in Production Management Systems, pp. 46-54, 2020.

[21] A. W. Colombo, S. Karnouskos, and T. Bangemann, “A System of Systems view on Collaborative Industrial Automation,” Proc. IEEE Intl. Conf. on Industrial Technology, pp. 1968-1975, 2013.

[22] S. Beer, “The Brain of the Firm,” 2nd Ed., Wiley 1981.

[23] J. Martin, J. Axelsson, J. Carlson, and J. Suryadevara, “Towards a Core Ontology for Missions and Capabilities in Systems of Systems,” to appear in Proc. IEEE Systems of Systems Eng. Conf., 2023.

[24] R. K. Yin, “Case Study Research: Design and Methods”, Sage, 2003.

[25] National Research Council, "Disaster resilience: A national imperative," 2012.

[26] S. Duchek, “Organizational resilience: a capability-based conceptualization,” Business Research, Vol. 13, pp. 215–246, 2020.

[27] H. Dittfeld, D.P. van Donk, and S. van Huet, "The effect of production system characteristics on resilience capabilities: a multiple case study", Intl. Journal of Operations & Production Mgmt, Vol. 4,2 No. 13, pp. 103-127, 2022.

[28] CMMI Product Team, "CMMI for Development, Version 1.3," Software Engineering Institute, Carnegie Mellon University, Technical Report CMU/SEI-2010-TR-033, 2010.

[29] R. H. Coase, “The Nature of the Firm”, Economica, Vol. 4, No. 16, pp. 386-405, Nov. 1937.

[30] J. Axelsson, J. Fröberg and P. Eriksson, “Architecting systems - of - systems and their constituents: A case study applying Industry 4.0 in the construction domain,” Systems Engineering, Vol. 22, No. 6, pp. 455-470, 2019.