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Procedia CIRP 80 (2019) 637–642

www.elsevier.com/locate/procedia

26th CIRP Life Cycle Engineering (LCE) Conference

Exploring the Opportunities of System of Systems Engineering to Complement Sustainable Manufacturing and Life Cycle Engineering

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Abstract

Increased digitalization leads to an overlap of technical systems, their surrounding environment and their embedded systems. The concept System of Systems (SoS) progressively emerges, offering the potential to contribute to sustainable development. A SoS bundles the capabilities and resources of its subsystems and, through intelligent collaboration, offers more functionality than the sum of its sub-systems. The current research on SoS is rather fragmented and there is still an open discussion on basic taxonomic and ontological issues. One important topic being discussed is the applicability of SoS Engineering (SoSE) to other related research disciplines. In this paper, we examine the interrelations of sustainable manufacturing, Life Cycle Engineering (LCE) and SoSE. Therefore, we provide a typology and a process-oriented framework for the integration of SoSE as a complementary discipline within the context of sustainable manufacturing and LCE.

Keywords: System of Systems Engineering, Life Cycle Engineering, Sustainable Manufacturing, Framework

1. Introduction

Within the last twenty years, research on the engineering of complex system architectures has gained significant importance [1]. Especially the trend towards digitalization increasingly connects different systems (e.g. products, machines or factories) to their environment, creating systems in which the interactions of different system entities can be considered as being part of a larger complex system. In general, a system is defined as "a composition of entities, which may be physical, behavioral, or symbolic in nature, that are interrelated, interdependent, and mutually interacting" [2]. If these entities are themselves regarded as systems, a system of systems is created (SoS). A SoS bundles the capabilities and resources of different systems and, because of intelligent collaboration, offers more functionality than the sum of the individual systems it consists of (emergent behavior). In Fig. 1, a generic representation of a SoS is illustrated. Here, central systems of interest (SoI, A and B) are differentiated from wider systems of interest (WSoI, C to E). SoI are in the focus of consideration to achieve a desired emergent behavior. WSoI are within the SoS environment and can enhance the existing emergent properties or provide additional emergent properties, when they are combined to the SoI. Thus, WSoI may get involved in a SoS and extend the boundaries of the original SoS.

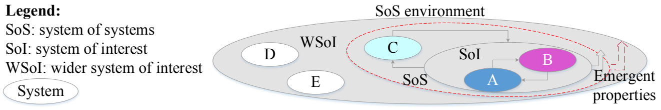

Fig. 1. Generic SoS architecture

From an engineering perspective, an essential question is how SoS can be designed in such a way that desired emergent properties are achieved and that chaotic behavior and unde-

10.1016/j.procir.2019.01.026

sired emergent properties are avoided [3]. Here, suitable methods and tools are required and can be found in the evolving research discipline System of Systems Engineering (SoSE). It stands for the "design, deployment, operation, and transformation of higher level [SoS] that must function as an integrated complex system to produce desirable results. These [SoS] are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography, and conceptual frame." [4].

Being first adopted in military applications [1, 5], SoSE has become vital in numerous application areas within the last twenty years. Examples can be found in the energy sector (e.g. power management) [6], transportation sector (e.g. air transportation) [7], industry sector (e.g. modern manufacturing systems) [8], disaster management (e.g. emergency information systems) [9], and further areas such as defense [10], health care, media [11], or communication [1]. As a result, the existing literature on this topic is rather fragmented and no acknowledged definitions for SoS and SoSE exist. In particular, there is an open discussion on what constitutes a SoS, what underlying paradigms or methodological approaches are and what the relationships of SoSE to other related research disciplines are, such as for example systems engineering [4], sustainable manufacturing [12] or LCE [13].

In this paper, we examine SoSE in order to understand how it can complement sustainable manufacturing and LCE, and whether and how it contributes to a sustainable development. Therefore, characteristics and types of SoS and methodological approaches to support their analysis, evaluation and engineering are given. We then discuss the relations of SoSE to sustainable manufacturing and LCE and provide a typology and framework to support the engineering of sustainable SoS.

2. Foundations of System of Systems Engineering

In order to provide guidance for SoSE, a common understanding of SoS is required. Although no acknowledged definition for SoS exist, there is agreement that all SoS have constituent characteristics. Fereidunian and colleagues provide a review of different characteristics mentioned in literature [14]. To evaluate whether or not a considered system is a SoS, a widely used set of characteristics is [15]: i) operational independence, ii) managerial independence, iii) geographical distribution of the involved sub-systems, iv) evolutionary development and v) emergent behavior of the SoS.

Besides the description of SoS by constituent characteristics, classification schemes exist (see Table 1). Seven SoS type dimensions can be differentiated, namely the objective, management, acquisition, operation, domain, durability and focus type. Table 1 provides a short description for each of them. Gideon and colleagues point out that one SoS can belong to more than one of the given categories [16].

In order to support the engineering of SoS, there are various activities which can be taken. Chen and Unewisse provide an overview on this variety, dividing SoS activities into SoS management, SoS design, SoS analysis and SoS integration [3]. For these activities a variety of approaches covering different methods and tools are discussed in literature. Existing approaches include e.g. design approaches [21], multi-level modeling [22], simulation approaches, e.g. agent-based [7, 8, 23] and discrete event simulation [23], petri-nets [14], optimization approaches [24, 25], analytical approaches [26], game theoretic approaches [27] as well as data analytics approaches [11]. Furthermore, architectural frameworks, such as the Department of Defense Architecture Framework (DoDAF), are used as pictoral representations using Unified Modeling Language (UML) or Systems Modeling Language (SysML) [28]. However, the approaches used in the context of SoSE have not been developed specifically for the use in this domain. They have been rather extrapolated or adapted from other engineering fields. Thus, so far no accepted methodological framework exists [1].

Table 1. Taxonomy of SoS, based on [16, 17, 18, 19, 20].

SoS type dimension	Criteria	Description
objective	*individual*	sub-systems follow individual objectives
	shared	sub-systems follow shared objectives
	global	sub-systems follow a global objective
management	*centralized*	central management
	collaborative	collaborative management
	local	local management of sub-systems
acquisition	*dedicated*	consciously designed and engineered to be an SoS and fulfill a certain goal
	virtual	systems are generally unplanned
operation	*directed*	controlled by a central authority
	chaotic	not controlled by a central authority
	collaborative	sub-systems can interact voluntarily
	acknowledged	similar to directed SoS, but they do not have the authority over the sub-systems
domain	*physical*	operate in the physical world
	conceptual	abstract and not tangible
	social	the main form of interaction is between people or organizations
durability	*permanent*	not expected to end
	episodic	deployed on demand
	prepared	prepared with a certain configuration before operation
	phased	prepared with several valid configurations being instantiated when required
focus	*capability–based*	collaboration interest based on capabilities
	function–based	collaboration interest based on functions
	service–based	collaboration interest based on services
	resource–based	collaboration interest based on resources

3. Opportunities of SoSE to complement Sustainable Manufacturing and LCE

Due to the ongoing discussion on the understanding of SoSE, exploring its connection to complementary and more established engineering disciplines can contribute to a more concrete picture of the advantages of a SoS perspective. Fig. 2 attempts to visualize the relations of SoSE to sustainable manufacturing and LCE.

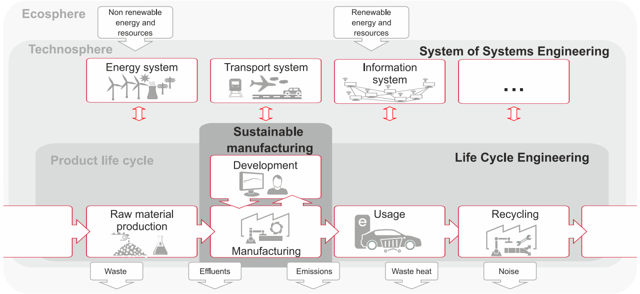

Fig. 2. Complementation of Sustainable Manufacturing and LCE by SoSE.

Sustainable manufacturing and LCE both strive for achieving sustainability, each having a different focus. Sustainable manufacturing focuses on a gate-to-gate perspective, taking a look on manufacturing systems. The focus is on methods, tools and technologies for the sustainability-oriented analysis, evaluation, planning and control of production systems and factories. Thereby, all subsystems of the factory (production machines and process chains, technical building equipment and building shell), all flows (material, energy, information) as well as their embedding in the (non-)urban context are considered [29]. Within LCE the sustainability implications of products and processes are evaluated on a life cycle perspective. The aim is to support engineering activities and related decision-making with respect to the design of products and the design of related material, energy and information flows. LCE involves life cycle assessment (LCA) which quantifies potential environmental impacts. The reduction of the environmental impact is a primary goal of LCE. [30] The focus of SoSE is broadened to not only consider the life cycle of a product or a product family as a foreground system (or SoI), but also on the simultaneous analysis, evaluation and design of systems in the background. This leads to the consideration of SoS. As a vision, this broader perspective could allow interdependent systems to simultaneously align towards a common goal: sustainability.

An important question is how SoSE can help to exploit the potential benefits that might result from a SoS perspective. Fig. 3 represents a generic relation of the environmental impact of different systems. On the left side, the environmental impact of the systems A to C is illustrated as the sum of their individual environmental impacts. On the right side, the environmental impact of the potential SoS is shown. Fig. 3 demonstrates that the building of a SoS is only viable from an environmental perspective if the environmental impact of the SoS is lower than the sum of the impacts of its constituent systems (A to C). Therefore, SoSE should focus on how SoS can be engineered in such a way that: (i) the building of a SoS has sustainability related emergent properties, e.g. by providing higher value from an environmental perspective whilst chaotic and unsustainable behavior is avoided, (ii) the integration of systems into a SoS affects the sustainability of other integrated systems positively. Hence, it is important to integrate the right systems to the right SoS so that a positive effect is achieved. At the same time the additional effort, for example for controlling the SoS, should not counteract potential advantages.

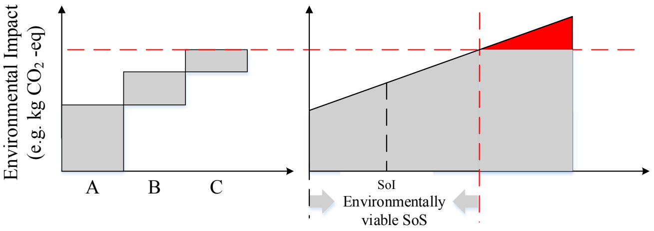

Fig. 3. Environmental Impact of SoS.

Whether or not SoS contribute to sustainability is of critical concern and has initially been discussed in literature. Katina and colleagues [31] propose a metasystem that governs a SoS while providing coordination, integration and viability of and for its constituent systems. However, they agree that methods and tools to support and guarantee the sustainability of SoS are still under development.

Having the relations of sustainable manufacturing, LCE and SoSE in mind, it is possible to derive a generic SoS typology, which can be used to propose environmentally viable SoS. As a first step, we suggest to consider four types of systems: product systems (e.g. vehicles, machines, etc.), infrastructure systems (e.g. road infrastructure, energy infrastructure, etc.), life cycle phase related systems (e.g. raw material production, manufacturing, etc.) and information systems (e.g. digital platforms, Enterprise Resource Planning (ERP) systems, etc.). A SoS can be built out of at least two of these system types, whereas each of the four types may count from 0 (or 1 for life cycle phase related systems) to N entities. Table 2 shows the resulting options.

Table 2. Typology of SoS.

System type	No. of entities Min	 max
Product system	0	N
Infrastructure system	0	N
Information system	0	N
Life cycle phase related system	1	N

In order to achieve a sustainable SoS, the system types must be integrated in such a way that the environmental impact of the resulting SoS is lower than the sum of the environmental impacts of the constituent sub-systems. Based on the typology, new SoS may be built or existing SoS may be analyzed in order to reduce the overall environmental impact. Three examples are shown exemplarily in Fig. 4. The types are related to the SoS architecture and the systems A to E in Fig. 1 and differ in their integration approaches to reduce the environmental impact of the resulting SoS. The three types are described below, referring to the approach to reduce the environmental impact, examples as well as opportunities for SoSE to support the reduction of the environmental impact.

Type I: Multiple life cycle related systems of one product system are integrated to reduce the environmental impact over the life cycle of a considered product system. Examples are closed-loop supply chain management [32] and approaches of circular economy using industry 4.0 technologies to make better choices with regard to recycling options (recycling 4.0)

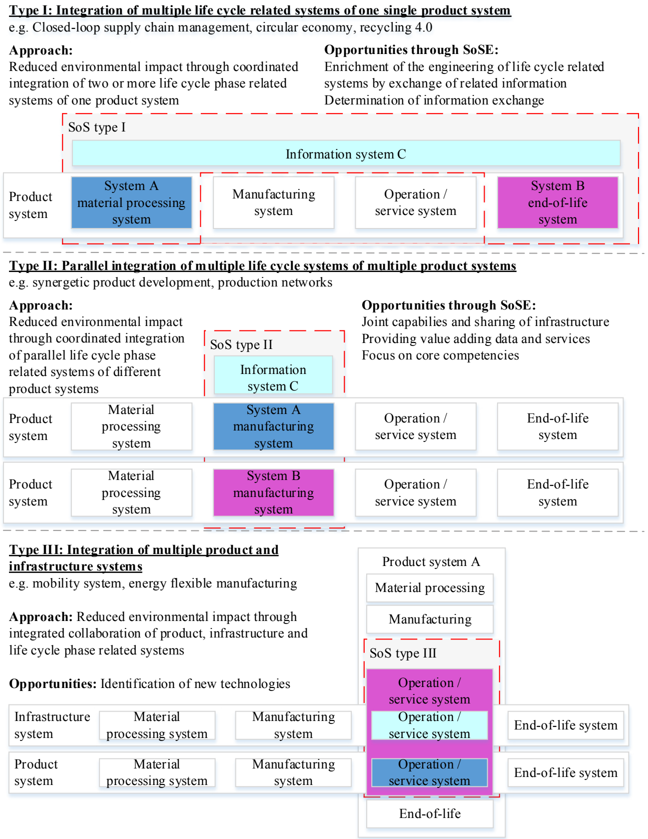

Fig. 4. Generic SoS types (exemplary)

[33]. An independent information system C (e.g. an ERP system) provides coordination and interrelates life cycle phase related systems. Through the knowledge gain of system C with regard to life cycle interactions of the product system, system C might provide further value adding services to other systems in the SoS environment. SoSE may support the integrated engineering of the life cycle related systems through targeted information exchange and the determination of information interfaces between the systems.

Type II: A reduced environmental impact is achieved through the coordinated collaboration of parallel life cycle phase related systems of multiple product systems. Examples are a synergetic product development [34], as well as collaborative purchasing or production networks [35]. Again, an independent information system C might be used to coordinate the activities of the life cycle related systems. Consequently, SoSE may help to extend the capabilities of single enterprises through shared knowledge and infrastructure and providing valuable data and services beyond enterprise boarders.

Type III: The integration of different product systems and one infrastructure system in one life cycle phase related system helps to reduce the environmental impact of one product system. Two examples are electric mobility [36] and energy flexible manufacturing [37]. In both cases the use of renewable energy might contribute towards lower environmental impacts, e.g. via the charging of electric vehicles with renewable energy, or helping to match the dynamic energy demand with the volatile on-site generation of renewable energy sources. SoSE may help to identify innovative technology options for the use in SoI to reduce the environmental impact.

The presented SoS typology does not claim completeness as further system types may be considered. Also, the potential contribution to achieve a sustainable SoS have to be verified using established methodologies, such as LCA. However, the given types may help SoS engineers in pre-structuring SoS problems and guide them for further system analysis in the context of sustainable manufacturing and LCE. Still, the setting of system boundaries for SoS clearly depends on the goal and scope of an engineering process, thus showing a need for further research on generic system typologies.

4. Towards a framework for the planning of SoS to complement sustainable manufacturing and LCE

Building on the knowledge of the interrelations of sustainable manufacturing, LCE and SoSE we propose a process-oriented approach to support SoSE (see Fig. 5). It provides guidance and support to conceptualize new SoS as well as categorize and improve existing SoS. Therefore, it integrates information on the characteristics and types of SoS, methodological approaches (see section 2) as well as the interrelations of SoSE, sustainable manufacturing and LCE. Starting point is a SoSE process with six steps, which are related to the layers of the framework and described below.

I) Definition of SoS goal and SoS characteristics: Once an engineer plans to conceptualize a new or improve an existing SoS, the first step is to define the goal of the SoS. The overall aim is to develop a SoS with sustainable properties which reduces the environmental impact of the constituent systems. In this regard, potential unsustainable behavior must be considered as well. Besides conceptualizing a new SoS, the consideration of existing systems can be of interest as well. Therefore, the constituent characteristics (section 2) can be used to qualify whether or not a considered system is a SoS.

II) Definition of SoS type: The SoS types refer to the classification schemes of SoS (see section 2). The SoS is described by the seven SoS type dimensions, namely: objective, management, acquisition, operation, domain, durability and focus.

III) Identification of the SoI: Based on the goal definition and the definition of the SoS characteristics, the systems that are needed to fulfill the goal(s) can be identified. Therefore, the SoI that complements sustainable manufacturing and LCE can be differentiated from WSoI outside these domains. As a first step, systems from the four categories product systems, infrastructure systems, information systems and life cycle related systems may be considered.

IV) Definition of SoS architecture & interactions: Based on the identified SoI and WSoI the SoS architecture & interactions are described. The system architecture helps to understand the life cycle interactions of the involved systems and to designate the interactions in terms of the types of relationship (e.g. information flows, material flows, etc.).

V) Description, analysis and evaluation of the SoS: Based on the system architecture, distinct methodologies are applied to further develop, evaluate and engineer the SoS. For a first description of SoS, architectural frameworks are useful. Modeling and simulation approaches help to describe and analyze the system behavior in more detail. Game-theoretic approaches help to understand the value systems of the involved actors

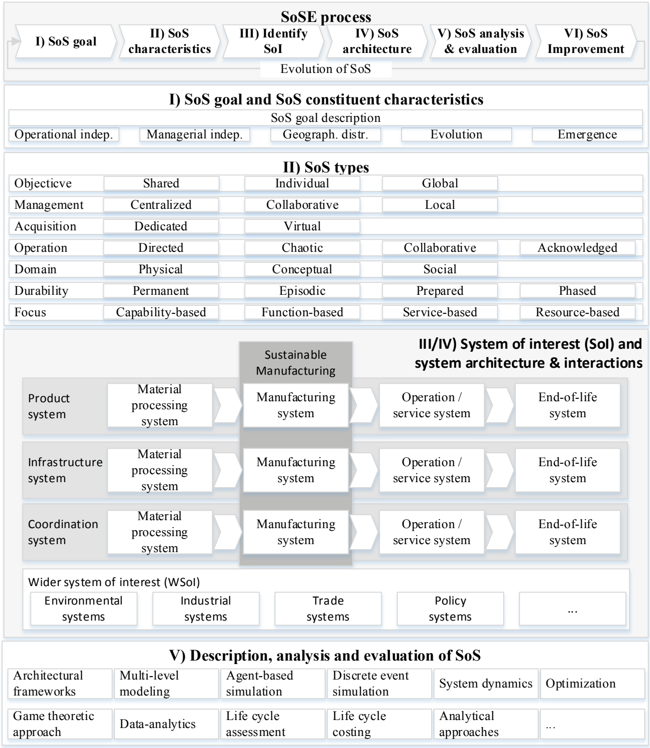

Fig. 5. Process-oriented framework for the planning of SoS.

and anticipate their behavior. The sustainability impact of the SoS can be evaluated using LCA and LCC approaches.

VI) Improvement of SoS: Based on the analysis and evaluation of the SoS, potential areas for improvement can be identified and integrated into the adaptation of the existing or the conceptualization of a new SoS. For example, it is possible to suggest the integration of further WSoI and/or change the interactions between involved systems. This could enhance the performance of the SoS with regard to sustainability and leads to the evolution of the SOS and step I) of the proposed process-oriented framework.

5. Case Study on Production Service Systems (PrSS)

The aim of the case study is to show how the typology and framework can be used to conceptualize a SoS in the context of sustainable manufacturing and LCE. To this end, the six steps of the framework are described for the development of a life cycle oriented Production Service System (PrSS).

I) Definition of SoS goal and SoS characteristics: The overall aim is to develop a SoS which contributes to sustainability. Therefore, a PrSS should be developed, which brings together manufacturing companies and service providers by means of a cloud and service platform for the exchange of data and services related to energy efficiency – an efficiency service cloud conceptualized as SoS. Data on the energy consumption of different machine systems is collected by sensor systems and provided to service providers. They offer value adding services based on available data (e.g. predictive maintenance).

II) Definition of SoS type: The SoS types are as follows: It is assumed that the involved systems have the global objective to contribute to sustainability in manufacturing. The management of the SoS is collaborative. It is dedicated and collaborative, as it is constructed to reduce the energy consumption in manufacturing, and the sub-systems can interact voluntarily. Furthermore, it is designed as a conceptual and permanent SoS and has a service-based focus using a cloud system as central data communication and service platform.

III) Identification of the SoI: The SoI are the manufacturing and operation/service systems of different product systems (systems A and B). For example, the product systems may refer to different vehicles, the manufacturing systems A may refer to their production systems, and the operation/service system B relates to the sensor systems. System C, the cloud system, provides the connection between the systems A and B. As data and services could support the engineering over the whole life cycle, e.g. by providing recommendations for the change in product design, the material processing system and the end-of-life system are categorized as WSoI. For simplicity, they are not considered in more detail.

IV) Definition of SoS architecture & interactions: In Fig. 6 the SoS architecture is displayed. This includes the exemplary product systems, their manufacturing systems, the operation / service systems of different sensor systems and the connecting cloud system. Several combinations of machine and sensor systems provide data on energy consumption for the cloud system. Based on this data, actors from the operation / service system may provide value-adding services to improve energy efficiency within the manufacturing systems. Furthermore, they may define requirements for data quality or new data-based life cycle services which are provided to the cloud and further to the manufacturing systems to evolutionary develop the system architecture (e.g. by providing new sensor systems). For simplicity, the interactions with WSoI are not considered in more detail.

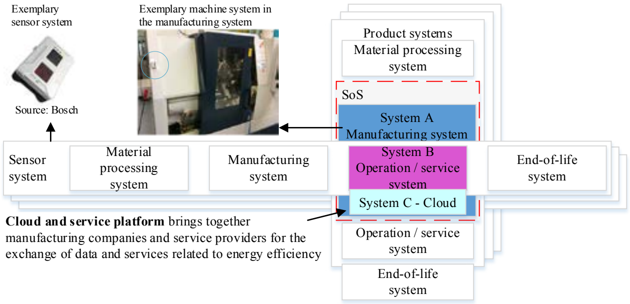

Fig. 6. Exemplary SoS architecture for PrSS.

V) Description, analysis and evaluation of the SoS: Next, the PrSS can be described by a more detailed architectural framework model. Modeling and simulation approaches could help to analyze efficiency potentials. Game-theoretic and business modeling approaches can be used in order to provide an understanding of the interactions of the involved actors and to gain insights for the development of business models for the PrSS. Using LCA and LCC, the sustainability impact of the SoS can be evaluated. In this regard, Thiede [38] analyzes the sustainability of cyber physical production systems in detail, having a close relation to the conceptualized efficiency service cloud.

VI) Improvement of SoS: Based on the analysis and evaluation of the PrSS, improvement measures can be derived. For example, the material processing system or end-of-life system can be involved in order not only to improve energy efficiency in manufacturing, but also in other life cycle stages.

6. Discussion and Outlook

In this paper, we discussed the interrelations of sustainable manufacturing, LCE and SoSE. Based on the foundations of SoS we developed a typology and a process-oriented framework to support the planning of SoS in the context of LCE and sustainable manufacturing. The paper contributes to the ongoing discussions on SoS by giving a more concrete picture of the potential advantages of a SOS perspective in respect to LCE and sustainable manufacturing. Still, the benefits of a SoS perspective with regard to sustainability have to be verified. Further research needs comply, inter alia: (1) the verification of systems to be SoS, (2) the development of generic system architectures and typologies for SoS, (3) the provision of more distinct criteria to characterize SoS, (4) the development of methods and tools to support SoSE, (5) the setting of system boundaries for SoS, and (6) the question on how to evaluate and guarantee the sustainability of SoS.

References

[1] Keating C, Katina, P. Systems of systems engineering: Prospects and challenges for the emerging field. Int. J. of System of Systems Engineering 2011. 2. p. 234-256.

[2] Hipel KW, Fang L, Bristow M. System of Systems Thinking in Policy Development: Challenges and Opportunities. In: Contemporary issues in systems science and engineering. Zhou M, Li H-X, Weijnen M editors. vol. 206. Hoboken, Wiley IEEE Press; 2015. p. 21–70.

[3] Chen P, Unewisse M. A Systems Thinking Approach to Engineering Challenges of Military Systems-of-Systems. Cmlth. of Australia. 2016.

[4] Keating C, Rogers R, Unal R, Dryer D, Sousa-Poza A, Safford R, Peterson W., Radabi G. System of Systems Engineering. In Engineering Management Journal 2003; 15 (3). p 36-45.

[5] Gorod A, Sauser B, Boardman J. System-of-Systems Engineering Management: A Review of Modern History and a Path Forward. IEEE Systems Journal Vol 2. No. 4, 2008. 484–499.

[6] Steghöfer J-P, Anders G, Siefert F, Reif W. A System of Systems Approach to the Evolutionary Transformation of Power Management Systems, in: Proceedings of INFORMATIK 2013 -- Workshop on "Smart Grids" 2013. p. 1500-1515.

[7] DeLaurentis DA, Ayyalasomayajula, S. Exploring the Synergy Between Industrial Ecology and System of Systems to Understand Complexity. Journal of Industrial Ecology 2009; 13 (2). p. 247–263.

[8] Zhou B, Dvoryanchikova A, Lobov A, Lastra JLM. Modeling system of systems: A generic method based on system characteristics and interface. In: 2011 9th IEEE Int. C. on Industrial Informatics; 2011. pp. 361–368.

[9] Liu S. Employing System of Systems Engineering in China's Emergency Management. IEEE Systems Journal 2011; 5 (2), p. 298–308.

[10] Siemieniuch CE, Sinclair MA. Extending systems ergonomics thinking to accommodate the socio-technical issues of Systems of Systems. Applied ergonomics 2014; 45 (1), p. 85–98.^

[11] Tannahill BK, Jamshidi M. System of Systems and Big Data analytics. Bridging the gap. Comp. & Electr. Engineering 2014; 40 (1), p. 2–15.

[12] Nahavandi S, Creighton D, Le VT, Johnstone M, Zhang J. Future Integrated Factories. A System of Systems Engineering Perspective. In: Integrated Systems. Innovations and Applications, Fathi M, editor: Springer, Cham; 2015. p. 147-161.

[13] Kobayashi H, Matsumoto T, Fukushige S. A simulation methodology for a system of product life cycle systems. Advanced Engineering Informatics 2018. 36. p. 101-111.

[14] Fereidunian A, Lesani H, Zamani, MA, Kolarijani, MAS, Hassanpour N, Mansouri SS. A Complex Adaptive System of Systems Approach to Human-Automation Interaction in Smart Grid. In: Contemporary issues in systems science and engineering. Zhou M, Li H-X, Weijnen M, editors, vol. 36. Hoboken, Wiley IEEE Press, 2015. pp. 425–500.

[15] Maier MW. Architecting principles for systems-of-systems. Syst. Engin. 1998; 1 (4), p. 267–284.

[16] Gideon J, Dagli CH, Miller A. Taxonomy of Systems-of-Systems. 2005.

[17] Allison J, Cook S. The New Era in Military Systems Thinking an Practice. In: Proceedings of Systems Engineering 98, Systems Engineering Society of Australia. 1998. p. 11-19.

[18] Maier MW, Rechtin E. The art of systems architecting. 2nd ed. Boca Raton, Fla: CRC Press. 2000.

[19] Dahmann JS, Baldwin KJ. Understanding the Current State of US Defense Systems of Systems and the Implications for Systems Engineering. In : 2nd Annual IEEE Systems Conference, 2008. p. 1–7.

[20] Garnier, J-L. Investigating in SoS Taxonomies to improve Systems Engineering. IEEE SoSE Conference, 2018.

[21] Hu L, Yongliang T, Yuan G, Jinpeng B, Jiangan Z. System of systems oriented flight vehicle conceptual design: Perspectives and progresses. Chinese Journal of Aeronautics. 2015; 28 (3), p. 617–635.

[22] Pushpendra K, Rochdi M, Blaise C, Belkacem O-B. Multilevel Reconfiguration Strategy for the System of Systems Engineering: Application to Platoon of Vehicles. In: IFAC Proceedings 2014; Vol. 47 (3). p. 8103–8109.

[23] Baldwin WC, Sauser B, Cloutier R. Simulation Approaches for System of Systems: Events-based versus Agent Based Modeling. Procedia Computer Science 2015; 44. p. 363–372.

[24] Konur D, Farhangi H, Dagli, CH. On the Flexibility of Systems in System of Systems Architecting. Proc. Comp. Sc. 2014; 36. p. 65–71.

[25] Farhangi H, Konur D, Dagli CH. Multiobjective System of Systems Architecting with Performance Improvement Funds. Proc. Comp. Sc. 2016; 95. p. 119–125.

[26] Choi T, Shen B. A system of systems framework for sustainable fashion supply chain management in the big data era. In: 2016 IEEE 14th Int. C. on Industrial Informatics (INDIN); 2016. p. 902–908.

[27] Hipel KW, Obeidi A, Fang L, Kilgour DM. Sustainable Environmental Management from a System of Systems Engineering Perspective. In: System of systems engineering. Innovations for the 21st century. Jamshidi M. editor. Hoboken: Wiley, 2009. p. 443–481.

[28] Delgado DJ, Torres-Sáez R, Llamosa-Villalba R. Develop an Executable Architecture for a System of Systems: A Teaching Management Model. Procedia Computer Science 2014; 36. p. 80–86.

[29] Herrmann C, Schmidt C, Kurle D, Blume S, Thiede S. Sustainability in manufacturing and factories of the future. Int. J. of Precis. Eng. and Manuf.-Green Tech. 2014; 1 (4), p. 283–292.

[30] Hauschild MZ, Herrmann C, Kara S. An Integrated Framework for Life Cycle Engineering. Procedia CIRP 2017; Vol. 61, p. 2-9.

[31] Katina, PF, Despotou G, Calida BY, Kholodkov TK, Keating CB. Sustainability of systems of systems. Int. J. System of Systems Engineering. 2014; 5 (2), p. 93-113.

[32] Quariguasi JFN, Walther G, Bloemhof J, Van Nunen JAEE, Spengler T. From closed-loop to sustainable supply chains: The WEEE case. Int. J. of Production 2010; 48 (15). Research, Taylor Francis, p. 4463-4481.

[33] ArL Braunschweig. Recycling 4.0. Digitalisierung als Schlüssel für die Advanced Circular Economy am Beispiel innovativer Fahrzeugsysteme. 2018. URL: http://www.suedniedersachsenprogramm.niedersachsen.de/startseite/presse/service/impressum-137190.html

[34] Vietor T, Herrmann C, Spengler TS (editors): Synergetische Produktentwicklung. Unternehmensübergreifend erfolgreich zusammenarbeiten. Ergebnisse des Verbundprojekts SynProd. Aachen: Shaker 2015.

[35] Herrmann C, Bergmann L, Halubek P. Production Management in SME Networks - Evaluation of Potentials and Achievements. In: Manufacturing Systems and Technologies for the New Frontier. Mitsuishi M, Ueda K, Kimura F, editors. Springer, London, 2008, p. 97-102.

[36] Herrmann C, Mennenga, M, Böhme S (Editors). Fleets go green. Cham: Springer International Publishing, 2018.

[37] Beier J, Thiede S, Herrmann C. Energy flexibility of manufacturing systems for variable renewable energy supply integration: Real-time control method and simulation. J Clean Prod 2017; 141, p. 648–661.

[38] Thiede, S. Environmental Sustainability of Cyber Physical Production Systems, in: Procedia CIRP 2018; Vol. 69, p. 644-649.