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Using model-based systems engineering (MBSE) and SysML for integrated sustainable manufacturing

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ABSTRACT: This article motivates the use of MBSE and SysML for organizational development and argues for a model-based integration of sustainable leadership (SL) into sustainable manufacturing (SM). We discuss whether modeling requirements resulting from SM and SL literature can be met by SysML and introduce an initial black box perspective and meta-model. The work is part of a larger research project aiming to transfer findings from SM and SL research into a model-based integrated SM in order to support a human-centered perspective. This work shows that SysML is suitable for organizational use cases.

KEYWORDS: model-based systems engineering (MBSE), socio-technical systems, SysML, sustainable leadership, sustainable manufacturing

1. Introduction

Design science enables a broad spectrum of creative and scientific solution developments. The design science research methodology (DSRM) according to Hevner (2007) and Peffers et al. (2007), defines methodological steps and three cycles (relevance, rigor and design) to ensure scientific artifact design. These scientific artifacts can include system models created by means of systems engineering (SE). SE aims to analyze and demonstrate entities, interrelationships, dependencies, and dynamics of systems to capture their complexity. This enables a holistic perspective without reducing systems to separate segments. Model-based systems engineering (MBSE) supports systems thinking and enables the development of complex system models. MBSE provides methods, tools, and languages that support the design, communication, and simulation of (socio-)technical systems (INCOSE, 2015). Beside technical elements, this can also include the mapping of roles, tasks and processes (Haberfellner, 2019).

Sustainable manufacturing (SM) describes a socio-technical system, that aims at achieving the three dimensions of the triple bottom line (TBL), i.e., environmental, economic and social sustainability in manufacturing. SM research often focuses technology-oriented issues and largely neglects social aspects (Henao et al., 2021; Jamwal et al., 2021; Martín-Gómez et al., 2024). This is a misguided approach, as the social well-being of employees is important for the successful implementation of SM and the pursuit of sustainable development (Ahuja et al., 2019; Gbededo & Liyanage, 2018). Leadership plays a decisive role in SM, but is hardly considered in the scientific discourse (Dubey et al., 2015; Hariyani et al., 2022; Vinkhuyzen & Karlsson-Vinkhuyzen, 2014). However, the human dimension including motivation, culture, values, and needs are crucial to SM processes and managerial success (Snyder et al., 2024; Sutherland et al., 2016). The field of sustainable leadership (SL) describes human-centered factors and requirements for leaders to promote sustainable development. It is based on ethics and values, and follows the TBL (Hallinger & Suriyankietkaew, 2018). SL can complement SM knowledge in terms of organizational development and broaden the field towards a human-centered leadership perspective (Nowak-Meitinger et al., in press). To develop a combined model that integrates SL into SM, an appropriate design approach is needed (Nowak-Meitinger et al., in press).

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Since neither SM nor SL offer a standardized and formalized modeling language for representing complex relationships, we strive for a modeling approach that captures the complexity of systems and ensures clarity in their representation. This requires a methodical approach and a formal modeling language. We aim to design artifacts that strengthen the social and human perspective in SM and uncover leadership needs with their integral components. In this context, this paper presents MBSE and the System Modeling Language (SysML) as a suitable solution. The following research questions are addressed:

- *Is SysML suitable to support the development of a model that integrates SL into SM?*
- *How can MBSE support the development of such an integrated model?*
- *Which new stereotypes and extensions are needed to represent the system of interest?*

In order to answer these research questions, section 2 first presents literature on SM and SL. The modeling gap is identified. This is followed by the description of the methodological context and the evaluation of the suitability of SysML by assessing the fulfillment of requirements derived from literature. Section 3 outlines the MBSE modeling approach and introduces a black box perspective as well as an initial meta-model. Finally, we discuss our findings in section 4 and draw conclusions in section 5.

2. Material and methods

The following literature review on the modeling of SM systems and SL frameworks leads to requirements for a new, integrated modeling approach, which is described subsequently.

2.1. Sustainable manufacturing systems and their representation in models

Sustainable manufacturing (SM) is a multi-layered discipline that examines the aspects, factors and structures of sustainable products and their manufacturing. Its aim is to reduce the negative impact on the environment and to avoid any negative social impact, e.g., ensuring operational safety and improving personal health (Jawahir et al., 2013). This is realized through the value creation factors (VCF), i.e., product, process, equipment, organization and human (Seliger, 2007). SM deals with sustainability in all product life cycle stages (pre-manufacturing, manufacturing, use and post-use) and implements the 6R value recovery strategies (reduce, reuse, recycle, recover, redesign, and remanufacture) (Badurdeen & Jawahir, 2017; Jawahir et al., 2013; Jayal et al., 2010). To address this complexity, frameworks and measurement systems are developed that include requirements for sustainable solutions. Although SM is a socio-technical system based on the three sustainability dimensions, research often neglects the social perspective (Henao et al., 2021; Jamwal et al., 2021; Martín-Gómez et al., 2024). Nevertheless, a human-centered perspective and socio-technical systems thinking are needed to progress SM (Davis et al., 2014). Further, SM assessment methods are typically not designed to consider interdependencies of the three sustainability dimensions and thus they are either segmented or processed in a sequential order and do not support effective decision-making for sustainable development (Gbededo et al., 2018).

To determine the current state-of-the-art in the modeling of SM systems, we conducted a literature search on SM in the Scopus and Web of Science databases. We focused on review articles on the concept of SM as well as on holistic frameworks and models. We used the search terms “sustainable manufacturing”, “model”, “framework” and “concept”. Furthermore, with the aim of expanding SM in the area of leadership, we combined “sustainable manufacturing” and “sustainable leadership” in our search and added related terms such as “enterprise”, “factory”, “leader”, “human”, “people”, “social”, “ethic”, and “responsibility”. We selected frameworks and modeling approaches that visualize general SM factors and their relationships and effects. The selection aims to highlight the diversity in the field by presenting different modeling approaches and languages with their respective strengths and weaknesses. We finally selected 18 representative articles that present modeling approaches related to our modeling goal (Table 1). The literature review shows that SM literature widely lacks MBSE applications with formal modeling languages such as SysML. This leads to difficulties in visualizing complexity and thus to partially unclear models or frameworks.

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Table 1. Literature review on frameworks and modeling of SM systems

ID	Reference	Key findings and modeling goal	Modeling strengths and advantages	Modeling gaps and weaknesses
1	Agote-Garrido et al. (2023)	Theoretical model for the design of SM systems in Industry 5.0.	Multi-layered and multi-perspective representation of SM.	Non-formalized modeling language
2	Amrina et al. (2016); Awan et al. (2018); Malek and Desai (2019); Subramanian and Suresh (2022)	Interpretive Structural Modeling (ISM) on: sustainability barriers in manufacturing firms; SM enablers; KPIs; and social sustainability factors in SM.	ISM models show interrelationships, dependencies and cause-effect relationships.	The ISM models do not provide a larger contextualization and require further text descriptions.
3	Fantini et al. (2013)	Reference model for SM to improve social sustainability.	The model represents a holistic perspective on social sustainability.	No formalized layer definition.
4	Henao et al. (2021)	Social performance metrics framework that maps different timescale levels to internal and external areas, with social metrics listed in different clusters.	This presentation provides a solid overview.	No links to other sustainability dimensions and assignments to product, process, or organizational structure included.
5	Jain and Kibira (2010); Thirupathi et al. (2019); Hao Zhang et al. (2013)	System Dynamics is used to describe causal effect structures in SM.	Models contain causal effect structures with directional information to describe dynamics.	Cross-level and multiple-factor representations are difficult to grasp.
6	Jamwal et al. (2021)	MCDM based framework for SM practices.	Different layers included.	Interrelations of factors remain unclear.
7	Martín-Gómez et al. (2024)	Characterization of industrial metabolism for design circularity in manufacturing systems.	Includes clustering, multiple levels, illustrations, and symbols.	Graphical representation is limited.
8	Nakano (2010)	Explore how SE can describe supply chains in SM and their risks.	Use of SE for SM, feasibility conceptually shown.	No specific, in-depth, MBSE model created.
9	Ocampo (2015)	A model to represent SM sustainability indicators.	The hierarchal structure is useful.	The graphical and tabular form is limited.
10	Ocampo and Clark (2015)	Integrative framework to develop a SM strategy.	Different layers and process steps included.	Interrelations of elements remain unclear.
11	Psarommatis and Bravos (2022)	Holistic framework for achieving sustainable manufacturing with zero defects and zero waste.	Consideration of pillars, processes and layers, highlighted in colored boxes.	Non-formalized modeling language lacks adaptability and scalability.
12	Sulistiarini et al. (2018)	Sustainable development strategy model for the manufacturing industry as a framework and guideline to support SM implementation.	Comprehensive model structured into strategy principles, indicators, and structure at management and operational level.	The presentation in tabular form has its limitations, the added graphical representation is not clear.
13	Heng Zhang et al. (2015)	Process-oriented information model using UML to simulate products and processes in SM.	Formalized language, includes a large amount of information.	Only visualization of product and process level.

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2.2. Sustainable leadership and its visualization in frameworks

Literature on *sustainable leadership (SL)* provides theoretical and empirical insights on leadership for sustainability and an inherently sustainable, i.e., social and human-centered, leadership. Using the search terms "sustainable leadership", "sustainability leadership", "regenerative leadership", "model", "framework" and "concept" we identified relevant literature in the Scopus and Web of Science databases. SL includes moral and responsible leadership and provides frameworks and cause-effect relationships that present information and recommendations for leaders and organizations striving for sustainable performance. SL describes factors and needs that enhance sustainable development and is based on ethics and values, such as prudence, mutual respect, value of individuals, innovation, and quality (Hallinger & Suriyankietkaew, 2018). SL characteristics include long-term vision; far-reaching goals that connect organizations with society; social responsibility of leaders and organizations; ethical behavior; ability to innovate; systemic change; and engagement and skills development of stakeholders (Hallinger & Suriyankietkaew, 2018). SL is presented in the form of plain text and simplified graphical frameworks. Avery and Bergsteiner (2011) created a commonly recognized SL pyramid with levels for SL practices, drivers and outcomes. Since there is no uniform definition of SL, a wide range of heterogeneous frameworks exist. Important aspects of SL include the consideration of context, stakeholder involvement and engagement, and a cultural perspective (Gerard et al., 2017; Hallinger & Suriyankietkaew, 2018). Further, SL categorization is made between personal and organizational aspects and skills (Armani et al., 2020; Fernandez et al., 2020) as well as between micro- and macro-levels in organisations (Galpin & Lee Whittington, 2012; Jayashree et al., 2022). Since SL is not uniformly defined, the term *sustainability leadership* is used synonymously in some cases, with frameworks being equally diverse and ambiguous, e.g., in Jayashree et al. (2022) and Sajjad et al. (2024).

In the related area of *Corporate Social Responsibility (CSR)*, multi-level frameworks to describe drivers and factors of CSR exist to ensure responsible organizational development. Examples show non-formalized modeling languages and limited representability in frameworks, as in Fallah Shayan et al. (2022) with an additional link to the Sustainable Development Goals (SDGs); Lozano (2015) with internal and external CSR drivers; Mukhuty et al. (2022) with the description of HR practices that enable socially responsible development of Industry 4.0; and Oliveira et al. (2023) with representing barriers. Common to all these organizational frameworks is the use of informal modeling languages, the lack of a uniform definition of SL, and a lack of clarity regarding structural levels and layers. SE and MBSE are not yet used for SL visualization and modeling.

2.3. Methodological context

This work is part of a larger design project that applies the DSRM consisting of a relevance cycle, design cycle, and rigor cycle (Hevner, 2007), to systematically develop a leadership model for SM (Nowak-Meitinger et al., in press). This article focuses the aspect of implementing a suitable modeling language as part of the design cycle. In this context, the preceding literature review on modeling SM systems and SL frameworks reveals the modeling gap. Below, we present a list of requirements that have been derived from the modeling approaches and frameworks in the literature. We examine the applicability and usefulness of SysML in the given context and propose to use MBSE for the artifact design. The MBSE Grid/MagicGrid 101 method (Aleksandraviciene & Morkevicius, 2021; Morkevicius et al., 2017) is a clearly defined and holistic method to develop systems and therefore selected for our study. The Dassault Systèmes CATIA Magic Systems of Systems Architect is used as MBSE tool. We present examples of the initial artifact design (section 3). However, the comprehensive rigor and relevance cycles, as well as the complete, detailed, and evaluated design artifacts, will be part of future work.

2.4. Using SysML to develop a leadership model for sustainable manufacturing

Our work aims to support the design of a leadership model for SM, i.e., describing and visualizing complex dependencies and relationships in SM to impact decision-making, behavior and mindsets of leaders. We do not focus on mathematical approaches, such as multiple criteria decision-making (MCDM). Instead, we aim to create clear visualizations that support leaders in identifying important aspects and dependencies that they need to consider and reflect on in their leadership behavior.

SysML is a modeling language used to specify, analyze, design, and verify complex systems (The Object Management Group® [OMG®], 2026). It is a powerful language that enables simulation and graphical modeling. To evaluate the suitability of SysML in comparison to existing modeling approaches in SM

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and SL, we derived a list of requirements from our findings in the literature review. Table 2 shows that SysML meets most of these requirements. Systems Dynamics [5] provides an alternative approach that leads to a different visualization and pursues modeling goals focusing cause-and-effect relationships and impact structures. The formalized modeling languages ISM [2] and UML [13] fulfill fewer requirements and are less suitable. The semi-formalized framework by Martín-Gómez et al. (2024) [7] and the basic SE approach by Nakano (2010) [8] are interesting for comparison.

The identified SL frameworks are non-formalized but support a leadership perspective that includes values, personal qualities, and organizational practices. SysML has not yet been used in SL theory. A related work deals with the modeling of leadership variables and their interrelationships (Latham, 2010). Research on SysML in the context of SM reveals that SysML can provide functional and logical models, such as architecture and schematic diagrams as well as physical, production and logistics models (Estridge et al., 2016). SysML can model data and processes including policies, procedures, and tacit knowledge (Estridge et al., 2016). As an information modeling language, SysML is particularly suitable for modeling the *Who*, i.e., stakeholders with their structures and requirements; the *What*, i.e., information and knowledge; and the *How*, i.e., processes of business systems (Pankowska, 2019). Taking this into account, the VCF of SM, i.e., product, process, equipment, organization, and human, can be modeled using SysML. Several studies on modeling organizational processes and structures in the field of manufacturing underline the feasibility and potential of our approach: Bataleblu et al. (2024) present a sustainable factory design using MBSE and SysML. Ahram and Karwowski (2013) present how sustainable complex systems can be engineered using SysML and computer-based design tools to build an information model. Zheng et al. (2024) develop an aircraft assembly process formalism and verification method including an ontology and object-oriented, clustered information and process models based on SysML. Fayoumi and Williams (2021) present an integrated socio-technical enterprise modeling without using SysML but including viewpoints, structures and factors.

Table 2. Meeting requirements through the use of SysML compared to existing modeling approaches

		Modeling of SM systems (ID from Table 1)													SL frame-
Requirement	**SysML**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**works**
Use a formalized modeling language	x	–	x	–	–	x	–	–	–	–	–	–	–	x	–
Enable multi-layered modeling	x	x	–	–	x	x	x	x	x	x	x	x	x	x	x
Provide a precise, clear, and complex representation of heterogeneous layers, levels, and categories	x	x	–	–	–	–	–	–	x	–	–	–	–	–	–
Visualize classification and relations between element types	x	–	x	–	x	–	x	x	x	x	–	–	–	x	–
Visualize hierarchal structures	x	x	–	–	x	x	–	x	x	x	x	x	x	x	x
Define system boundaries	x	–	–	x	–	x	–	x	x	–	–	–	–	–	–
Embed system in a context	x	–	–	x	x	x	–	x	x	–	x	–	–	–	x
Include different internal and external viewpoints/perspectives	x	–	–	–	–	x	–	x	x	–	–	x	–	x	–
Include a large amount of information	x	x	–	–	x	x	–	x	–	–	–	x	–	x	x
Provide self-descriptive elements	x	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Present interrelationships and impact structures comprehensibly	/	–	x	–	–	x	–	–	x	–	–	–	–	x	–
Use different colors	x	x	–	x	x	x	–	x	x	–	–	x	x	–	x
Use different boxes/shapes	–	x	–	x	–	–	–	x	x	–	–	–	–	–	x
Include symbols or figures if needed	x	x	–	x	–	x	–	x	–	–	–	–	–	–	–
Capture complexity	x	–	–	–	–	x	–	–	–	–	–	–	–	–	–
Provide scalability	x	–	–	–	x	x	–	x	x	x	–	–	–	x	–
Easy to adapt/apply to use cases	x	–	–	–	x	x	–	–	x	x	–	–	–	x	x

(*Continued*)

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Table 2. Continued

Requirement	SysML	Modeling of SM systems (ID from Table 1) 1	2	3	4	5	6	7	8	9	10	11	12	13	SL frameworks
Provide model simulation	x	–	–	–	–	x	–	–	–	–	–	–	–	x	–
Use of SE/MBSE	x	–	–	–	–	x	–	–	x	–	–	–	–	–	–
Support decision-making	x	x	x	–	x	x	–	–	x	x	–	–	–	x	x
Includes leadership behavior and elements for (self-)reflection	/	–	–	–	–	–	–	–	–	–	–	–	–	–	x

[x] requirement fulfilled, [/] requirement fulfillment to be evaluated, [-] requirement not fulfilled

3. Towards a model-based integrated sustainable manufacturing

In this section we present a meta-model to create the diverse functions and levels of SM and SL. SysML offers versatile meta-modeling and various model types that can be linked and nested within each other.

3.1. Procedure according to MagicGrid® and selection of modeling components

According to the *MagicGrid 101* method (Aleksandraviciene & Morkevicius, 2021; Morkevicius et al., 2017), modeling starts with the *problem domain*, divided into *black box* and *white box* to describe a system of interest (SoI) within its context. MagicGrid 101 pillars include *requirements, structure, behavior, and parameters*. These pillars allow a comprehensive description of the SoI with multiple perspectives. Since this method is primarily designed for technical systems, its application to our modeling goal requires a transfer and redefinition of typical modeling practices. However, MagicGrid 101 forms a guide for the modeling. In the following we describe the problem domain from a black box perspective. The white box and the solution domain with internal system elements and processes are considered in the outlook and will be specified in future work. Since the pillar s*afety and reliability* is not relevant to this work and the *implementation domain* it is not part of MBSE, both are neglected.

3.2. The black box perspective in the problem domain

Modeling the problem domain starts with capturing stakeholder needs (*requirements*), followed by describing the system context (*structure*). The SoI remains a black box in these steps, thus the interaction of the SoI with its context is focused on and the system boundaries are defined. Our work aims to identify and represent linkages between SL and SM, and to integrate SL practices into SM theory in order to broaden and deepen sustainable performance in SM. The modeling shall support the representation and accessibility of the results. This means that the SoI is a model that represents and supports leadership practices and processes in SM, but does not execute them directly. The execution remains with the people, i.e., leaders and independent employees. Stakeholder needs can be derived from SL and SM theory or other sources provided in the relevance cycle and rigor cycle of the DSRM. Stakeholder needs may include building a motivated, committed, capable, and healthy workforce, (self-)reflection on leadership behavior as well as high performance in sustainable practices and compliance with standards and guidelines for successfully passing audit processes.

The system context can include other systems such as the cultural, institutional, industrial, historical, and political context and be presented in an internal block diagram (ibd). Furthermore, context elements include users who are defined as different types of leaders, e.g., team leaders, department heads, division managers, and managing directors or project managers and independent employees. In this system context, use cases (*behavior*) are defined. Each type of leader can be associated with different use cases. These are modeled in use case diagrams (uc) and activity diagrams (act) and may include: reviewing the implementation of ethical values in organizational practices, improving the understanding and application of SL, and promoting a holistic implementation of SM. In the final step of the black box perspective, measures of effectiveness (MoE, *parameters*) are added as higher-level performance indicators. These MoEs are diverse and can include, e.g., employee satisfaction, well-being, motivation, performance, absenteeism, and audit success.

All elements modeled in the black box should be described as detailed as needed for users to receive relevant information. The white box will describe the SoI in its conceptual subsystems and functional

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analysis. Multiple levels are conceivable in the problem and solution domains. However, since this model design is a wicked problem (Rittel & Webber, 1973), in-depth analysis and elaboration of model components and their complexity does not claim to be complete. Due to its scalability, variations in the abstraction levels are to be elaborated in future work. It is important to note that in the design discipline, which lies between theory and practice, *practicality* is more important than *completeness* (Aicher, 2015). The focus of our work is on designing the model, i.e., transferring a complex, interdisciplinary knowledge base into a multidimensional SysML model with several levels, layers, and perspectives.

3.3. Meta-model using SysML

To start modeling, a meta-model with a preliminary selection of entities is created. The meta-model provides stereotypes that should be included in the model. Figure 1 lists blocks used for internal and external elements, relations to connect entities, and diagrams to represent different perspectives. Furthermore, requirements are categorized by their type and the model is managed through the use of legends. This overview is presented in packages that can include several entities. We recommend to start modeling according to MagicGrid 101 using these initial stereotypes and elements for SysML diagrams.

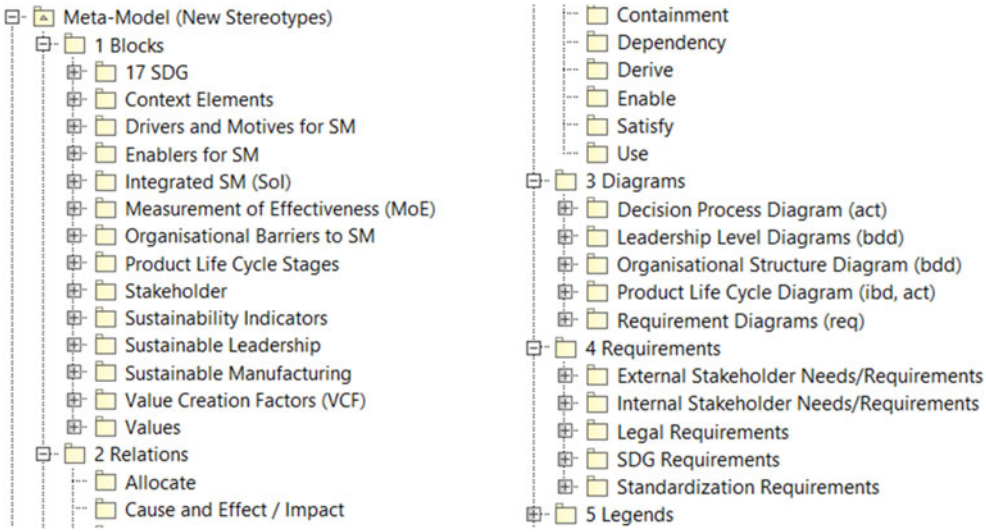


Figure 1. Meta-model with initial stereotypes

4. Discussion

To answer the first research question, we compared the suitability of the formal and adaptable modeling language SysML with existing modeling approaches in SM. To do this, we derived modeling requirements from the literature. The comparison shows that SysML stands out because it offers possibilities for clear, graphical representation of complex, multi-layered, and diverse systems. It can integrate descriptions for elements and relations and is flexible and scalable in its use. This leads to the effective implementation of SysML in SM with a human-centered leadership perspective.

The second and third research questions could be answered by describing a modeling approach using MagicGrid 101 and presenting an initial meta-model to design and implement a *model-based integrated SM*. The initial black box perspective demonstrates the feasibility of applying MBSE to SM and SL by the use of the MagicGrid 101 pillars *requirements, structure, behavior, and parameters*. However, a new interpretation and application of the MBSE methods, tools, and languages is required, since the conventional use in a technical context is not suitable. New paradigms and approaches are needed to ensure MBSE and SysML are usable for the purpose of supporting leadership practices in SM. The overview of new stereotypes in the meta-model forms a basis for creating conceptual design artifacts.

The first design steps presented in this study cover two important aspects: Firstly, the context perspective, because sustainable practices can only be fully implemented if leaders in SM take the context into account. Secondly, the application of systems thinking, which is based on the contextual perspective and system boundaries. Diagrams can be created that describe and link various levels, layers and perspectives. Model users can interactively navigate from one element to another, gaining a holistic view of the system.

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Future work will include detailed design studies and the evaluation of the resulting artifacts. Models will demonstrate how MBSE and SysML capture interrelationships and dependencies, and thus the resulting complexity of sustainability requirements and measures in SM combined with leadership aspects. Value-adding processes along the product life cycle and links to the organizational structure, i.e., roles and structures will be integrated in the modeling. The final model can serve as a guide for leaders and support the sustainable transformation of manufacturing companies.

Our work is currently based on SysML v1. Since the more compact SysML v2 is now also integrated into graphical tools, it may become relevant for future work. Applicability and transferability to SysML v2 should be considered in the model development as it may increase interoperability of the model. However, both SysML versions are functional and suitable for the modeling goal.

5. Conclusions

This paper introduces a MBSE and SysML modeling approach for sustainable manufacturing (SM) and sustainable leadership (SL) to support the visualization and communication of complex information in socio-technical systems. Since the fields of SM and SL are hardly interlinked and both are diverse and extensive, it is necessary to use a formalized and integrated modeling approach to capture complexity. Based on a literature review, modeling requirements were derived and SysML was evaluated as suitable. The applicability of MBSE is outlined from a black box perspective, and an initial meta-model includes SM and SL elements that are relevant for modeling. The design science research methodology (DSRM) frames this work. We focus on the design cycle with the aim of providing an approach that uses MBSE and SysML to capture SM and SL for designing a *model-based integrated SM*.

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