Metamodeling in Manufacturing Systems: Literature Review and Trends

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Abstract

Changing customer needs and short product life cycles, confront production systems with growing challenges, especially in terms of flexibility and production speed. To analyze the system behavior, mathematical models and models based on logical relationships are created. However, as manufacturing systems become more complex, these methods reach their limits, and simulation is increasingly used.
Simulation has gained relevance as a method of analysis. The potentials of simulation of manufacturing processes are contrasted by high efforts in the preparation and integration. Chances for increasing the efficiency of simulation studies can be seen in the conceptual model development, model generation and verification, and validation.
Metamodeling offers an approach for reducing the effort in the creation of simulation models by providing common syntax, semantics, or structural features. This work represents a structured literature review investigating current research work on metamodeling in manufacturing systems. Application areas and different types of metamodels are made visible and further research is suggested.

Keywords
Metamodeling; Manufacturing Systems; Process Modeling; Information Modeling; Simulation Modeling

1. Introduction
The manufacturing industry and factories of the future are facing increasing product variety, individualization, and high-quality requirements. Industry 4.0 technologies offer great opportunities to meet these demands, overcome challenges, and enhance competitiveness (Dallasega et al. 2020; Woschank et al. 2020a; Woschank and Zsifkovits 2020; Dallasega et al. 2019; Rauch and Vickery 2020; Egger et al. 2017). Moreover, in manufacturing systems Industry 4.0 proposes a collaborative architecture and enables the merging of the information technology domain and the operational technology domain. The concept of cyber-physical systems is setting the fundamentals for the smart factory (Rojas et al. 2017).
To generate insights into system behavior, models based on mathematical and logical relationships are formulated and analyzed. However, as the complexity of these manufacturing systems increases, analytical methods reach their limits, and simulation is increasingly used as a method of analysis (Law 2015; Gutenschwager et al. 2017). With advancing digitalization and the advent of the concept of the digital factory, simulation methods are gaining increasing importance. Simulation has become one of the most widely used decision support tools in manufacturing companies. The potential of material flow simulation for the analysis of existing manufacturing processes is contrasted by high efforts in the preparation and execution of simulation studies. Besides the necessity of simulation experts, the creation and integration of simulation involve considerable cost and time (Fowler and Rose 2004; Bergmann 2013). In particular, small and medium-sized enterprises seem to face these technical and economic barriers (Bracht et al. 2018). In this context, Fowler and Rose (2004) have identified challenges in the field of modeling and simulation of complex manufacturing systems. Among them, the reduction of time and effort in the phases for conducting a simulation study is shown. Especially in the area of conceptual model development, selection of modeling approach, model generation and verification, and validation. Fowler and Rose (2004) see great potential for increasing efficiency.
Recent literature (Grznár et al. 2020; Herrera et al. 2020; Yang et al. 2018) defines metamodeling as an approach for reducing the effort in model creation. Ontological metamodels can be applied to provide a consistent definition of the language needed to create a model. On the other hand, the term can be understood to be a model of models. In this

regard, a model can be defined by the specifications held in a metamodel (Kühne 2006). Overall, a metamodel offers common syntax, semantics, or structural features to facilitate modeling and simulation in a specific application domain by establishing a standard (Yang et al. 2018). In the context of techno-economics (Zunk 2018), the authors perform a structured literature review to investigate current research on the topic of metamodeling in manufacturing systems and identify application areas in this context.

2. Research Methodology

In this paper, the authors investigate current practices, evaluate recent research studies, and outline the potentials for the application of metamodeling in manufacturing systems.
To ensure a systematic procedure and limited bias, a structured literature review is selected as a research methodology (Petticrew and Roberts 2012; Booth et al. 2016). The purpose of the structured literature review is to identify and aggregate relevant studies and findings using a transparent and reproducible process. It is suitable for research topics that are characterized by studies diverse in terms of methods and theoretical approaches (Andreini and Bettinelli 2017). Literature offers a multitude of directives and practices to conduct the structured literature review (Bettany-Saltikov 2012; Littell et al. 2008; Andreini and Bettinelli 2017). In this paper, following Littell et al. (2008), Bettany-Saltikov (2012), and Woschank et al. (2020b) the following steps were applied:

- Definition of focus, scope, and central assumptions guiding the review
- Generating the meta-search query and data collection
- Scoping of references
- Full text screening and content-related clustering of references

2.1 Definition of Focus, Scope, and Central Assumptions

This paper deals with the topic of metamodeling and its application in the modeling and simulation of discrete manufacturing systems and aims to enhance the understanding of metamodeling and its relevance for industrial application. In a structured literature review, the current research work is analyzed to identify existing and emerging application areas for metamodels in the last years. The authors focus on manufacturing processes and the potential that arises in this context.
For the structured literature review, a keyword search is conducted in SCOPUS. The research work of recent years is evaluated and classified. To make application areas and different types of metamodels visible, the results of the search-query are clustered into subareas and described. Based on the identified subareas, a research direction and research gap will be indicted in the conclusion.
In the keyword search, the authors identified relevant publications for metamodeling in the subject areas of ‘engineering’ and ‘business, management, and accounting’ by screening titles, abstracts, and keywords. Further, the authors focused on studies in the areas of manufacturing and logistics. Limiting the identified publications to these criteria, setting the timeframe to the period of 2015 until 2020, and limiting to conference papers, articles, conference reviews, or reviews to ensure actuality and high quality of the publications, resulted in 192 identified publications. Subsequently, these records were reviewed and evaluated based on their relevance to the defined research objectives. Relevant papers were clustered according to their content. Finally, the following meta-search query was generated: (TITLE-ABS-KEY ("Simulation metamodel" OR "meta-modeling" OR "meta-modelling" OR "meta modeling" OR "meta modelling" OR "metamodeling" OR "metamodelling" OR "meta model" OR "metamodel" OR "metamodeling methods") AND TITLE-ABS-KEY ("manufacturing" OR "logistics" OR “production systems”)) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cr") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "BUSI")) AND LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015)) AND (LIMIT-TO (LANGUAGE , "English") OR LIMIT-TO (LANGUAGE , "German"))

2.2 Screening and Clustering of References

In the next step, a review of titles and abstracts was carried out to identify the relevant publications. During this process three main areas of topics were identified:

- Metamodeling in manufacturing systems and process design
- Metamodeling in product design
- Metamodeling in additive manufacturing

As displayed in Table 1, 87 papers were assigned to the area of metamodeling in manufacturing systems and process design, 44 were assigned to the area of product design, and 15 to the area of additive manufacturing.

Table 1. Total research results and areas

AREA	NO. PUBLICATIONS
Total studies	192
Metamodeling in manufacturing systems and process design	87
Metamodeling in product design	44
Metamodeling in additive manufacturing	15

In the subsequent steps, the papers assigned to the area of metamodeling in manufacturing systems and process design are considered.

3. Results

In this section, the authors outline the descriptive results of the structured literature review, as well as the content analysis of the studies in the field of metamodeling in manufacturing systems and process design. Therefore, the full texts of the identified papers are reviewed.

3.1 Descriptive Analysis

For the subsequent analysis, only the publications regarding metamodeling in manufacturing systems and process design were considered. The identified papers were labeled 'high', 'medium' and 'low' regarding their relevance for the research objectives. Table 2 displays the results of the labeling.

Table 2. Distribution of the relevance of papers in metamodeling in manufacturing systems and process design

RELEVANCE	NO. PUBLICATIONS	PUBLICATIONS (%)
Total studies	87	100
High relevance	33	37.93
Medium relevance	24	27.59
Low relevance	30	34.48

To evaluate the identified publications concerning their relevance to the research objective, the following questions were defined:

- Does the publication address process data or process information?
- Are activities or abilities of components underlying the process considered?
- Are relations within the process/system examined?

Based on whether these questions could be answered yes, no, or undecided, the papers were marked. Out of the identified 87 studies, 33 papers (37.93%) were classified with 'high relevance', 24 papers (27.59%) were classified with 'medium relevance' and 30 papers (34.48%) were classified with 'low relevance' regarding the research objectives.
Table 3 shows the distribution according to the type of document of a total of 87 identified papers. A share of 46 papers (52.87%) are conference papers, 40 (45.97%) are articles and 1 (1.16%) is a review. In the final sample, no conference review was identified.

Table 3. Distribution according to document types

DOCUMENT TYPE	NO. PUBLICATIONS	PUBLICATIONS (%)
Total studies	87	100
Conference papers	46	52.87
Articles	40	45.97
Reviews	1	1.16

Figure 1 shows the development of relevant research studies in the years 2015 to 2020.

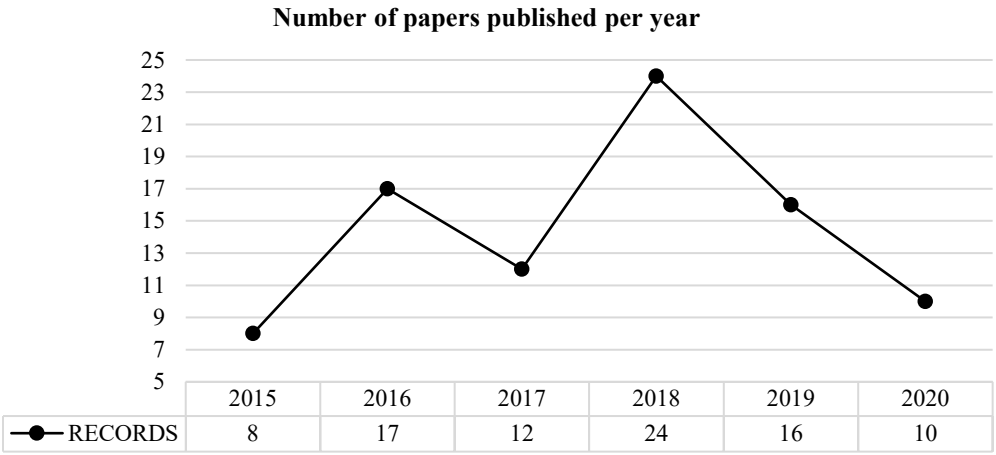

Figure 1. Development of relevant research studies 2015 - 2020

In the time frame from 2015 to 2018, a clear upward trend of relevant studies regarding the application of metamodeling in manufacturing systems and process design can be observed. Despite there is a decreasing trend in the research studies from 2018 onwards, metamodeling offers a broad application area and, therefore, a fruitful field of research.

3.2 Content Analysis

In the consecutive step, the content analysis and classification, only the papers labeled with 'high relevance' were examined. Finally, 33 studies were reviewed in this research step.
Based on in-depth content analysis, the authors defined the following five clusters of research areas:

(1) Metamodels fostering the coherent formal description of processes
(2) Metamodels describing process information exchange
(3) Supporting decision-making through metamodel-based analysis
(4) Metamodels facilitating the simulation of manufacturing systems
(5) Establishing modular material flow systems using metamodels

Table 4 gives an overview of these areas and the distribution of papers according to their cluster.

Table 4. Clustering of identified research studies

RESEARCH AREAS	NO. PUBLICATIONS	PUBLICATIONS (%)
Metamodels fostering the coherent formal description of processes	9	27.3%
Metamodels describing process information exchange	7	21.2%
Supporting decision-making through metamodel-based analysis	7	21.2%
Metamodels facilitating the simulation of manufacturing systems	6	18.2%
Establishing modular material flow systems using metamodels	4	12.1%

Table 5 summarizes the structured literature review and assigns each research study to the defined clusters.

Table 5. Results of the structured literature review on metamodeling in manufacturing systems

No.	Reference	Cluster	Content
1	(Ewa 2015)	Metamodels fostering the coherent formal description of processes	Proposes a formal modeling method of manufacturing processes including disturbances. The approach is based on a multi-stage dynamic decision process.
2	(Kathrein et al. 2019)	Metamodels fostering the coherent formal description of processes	Presents a metamodel to describe relations between product, process, and resource relations and offers a formal model to check validity and automating quality.
3	(Jakjoud et al. 2016)	Metamodels fostering the coherent formal description of processes	Introduces a system process engineering metamodel to address the lack of coherent models defining and representing the key concepts of processes.
4	(Richter et al. 2016)	Metamodels fostering the coherent formal description of processes	Presents a modeling technique for integrated requirements and systems modeling in the mechatronic development phase. The individual modeling contents are presented on a metamodel level and support the initial development phase.
5	(Romero et al. 2020)	Metamodels fostering the coherent formal description of processes	The authors conduct a systematic literature review to gather characteristics of Smart Systems. Based on the findings a metamodel of Smart Systems is designed.
6	(Brunoe et al. 2019)	Metamodels fostering the coherent formal description of processes	Presents an approach to establish models linking product domain and manufacturing domain. A metamodel for developing company-specific ontologies is proposed.
7	(Elfaham and Epple 2020)	Metamodels fostering the coherent formal description of processes	Introduces a concept to link logistics models with abilities. A metamodel describing logistics abilities of transport and handover is designed for enabling the description of possible paths for the material flow.
8	(Nishioka et al. 2016)	Metamodels fostering the coherent formal description of processes	Proposes a collection of reference models for manufacturing activities, information, and data entities to enhance collaboration of connected enterprises.
9	(Karagiannis 2018)	Metamodels fostering the coherent formal description of processes	Presents a framework to improve modeling method agility by complementing standard methods. The approach enhances responsiveness to dynamic needs within an Agile Enterprise.
10	(Yang et al. 2016)	Metamodel describing process information exchange	A hierarchical modeling approach is proposed to provide a systematic modeling framework for process planning and modeling manufacturing process information in synchronization with their data relationships.
11	(Hildebrandt et al. 2017)	Metamodel describing process information exchange	Focuses on semantic modeling of information in the production domain, providing a combination of a metamodel for modeling mechatronic systems and a metamodel for modeling the system's characteristics.
12	(Vlasenko 2019)	Metamodel describing process information exchange	Deals with the use of conceptual graphs theory for creating semantic metamodels. The use of this technique is discussed for representation and processing of knowledge models.
13	(Breckle et al. 2019)	Metamodel describing process information exchange	Introduces an approach of a Digital Factory containing and reporting generated information based on an open standard metamodel, aiming at a holistic data model.
14	(Gagliardi et al. 2017)	Metamodel describing process information exchange	Presents a metamodeling technique to determine input and output relationships in manufacturing applications. Using historical data on similar problems reduces time and cost efforts in the process reengineering phases.
15	(Lock and Reinhart 2016)	Metamodel describing process information exchange	Introduces a metamodel describing different types of interrelations of a production process and its support processes. The approach enables the investigation of influences between processes within a process system.
16	(Yang et al. 2018)	Metamodel describing process information exchange	Presents a systematic methodology for using metamodeling as basis for manufacturing process information modeling. The proposed method facilitates information exchange and software interoperability.

Table 6. Results of the structured literature review on metamodeling in manufacturing systems (continued)

17	(Sharma et al. 2017)	Supporting decision-making through metamodel-based analysis	Presents a metamodeling approach for providing approximate relationships between input parameters and output variables for machining processes. These models can be used for decision-making in the initial process development phase.
18	(Borovska et al. 2017)	Supporting decision-making through metamodel-based analysis	Addresses the optimization problem of sustainable development of production systems. On the basis of metamodels, the creation of mathematical models of developing production systems is suggested to assess risks and survivability.
19	(Lara et al. 2020)	Supporting decision-making through metamodel-based analysis	Presents a technique using operational data to model operation technologies, with the purpose of applying analysis methods. The produced information can allow insight into production performance and support accurate decision-making.
20	(Salama and Eltawil 2018)	Supporting decision-making through metamodel-based analysis	Proposes an architecture of an IoT based decision support system based on a simulation metamodeling optimization approach. The integrated framework assists the planning and operational control of cyber-physical production facilities.
21	(Utz and Falcioni 2018)	Supporting decision-making through metamodel-based analysis	Introduces the idea of providing a flexible, dynamically composed modeling method that supports managing the quality of multi-stage production systems. The approach combines, and harmonizes data streams within a heterogeneous environment.
22	(Lara et al. 2019)	Supporting decision-making through metamodel-based analysis	Proposes a metamodel that serves as a domain-specific modeling language to understand reverse logistics processes and apply analysis methods. By creating scenarios considering the main issues of reverse logistics these flows can be studied.
23	(Wagner et al. 2020)	Supporting decision-making through metamodel-based analysis	Presents the integration of a metamodel into the digital twin of a production system. With this approach, product knowledge is integrated into the production control, and the function-oriented production control is enabled.
24	(Grznár et al. 2020)	Metamodels facilitating the simulation of manufacturing systems	Describes the use of modeling and simulation processes in factories in the context of Industry 4.0. To simulate the emerging complexity the authors outline the method of using metamodels as possible solution.
25	(Merschak et al. 2018)	Metamodels facilitating the simulation of manufacturing systems	Defines a metamodel framework, using a combination of traditional simulation approaches to defining linkages between different system levels in cyber-physical production systems.
26	(Herrera et al. 2020)	Metamodels facilitating the simulation of manufacturing systems	Introduces the concept of metamodeling as basis for modeling, analysis techniques, and decision-making support. The proposed metamodel simplifies simulation modeling, correction, and improvement.
27	(Brovkina and Riedel 2019)	Metamodels facilitating the simulation of manufacturing systems	Presents a semantic metamodel for Cyber-Physical-Systems. A graph-based skill-description is given, which in combination with the appropriate manufacturing process description allows automatic matching for simulation and optimization.
28	(Greinacher et al. 2020)	Metamodels facilitating the simulation of manufacturing systems	Presents meta-models to approximate the system behavior and enable extensive multi-objective optimization and adequate decision-making.
29	(Werke et al. 2015)	Metamodels facilitating the simulation of manufacturing systems	Proposes an algorithm for simplified metamodeling of manufacturing sequences. Through using an upstream selection of process steps interconnected models are defined. The algorithm can be used for extracting virtual simulation sequences.
30	(Aicher et al. 2016)	Establishing modular material flow systems using metamodels	Presents a metamodel for an automated material flow system including standardized interfaces to enable code generation for control structures.
31	(Höfig et al. 2019)	Establishing modular material flow systems using metamodels	Introduces a metamodeling language supporting the automation of process failure mode and effects analysis. The metamodel allows to automate the design space investigation of possible process scenarios and to measure the impacts of changes.
32	(Regulin et al. 2016)	Establishing modular material flow systems using metamodels	Introduces a metamodel-driven approach for the development of modules for automated material flow systems. The aim is to improve transferability and consistency of information flows between engineering stages and plant planning.
33	(Brandenbourger et al. 2017)	Establishing modular material flow systems using metamodels	Describes a recursive metamodel-based concept to allow a structured generation of manufacturer-specific models of automation components. The concept facilitates seamless engineering between component and plant manufacturers.

3.2.1 Metamodels Fostering the Coherent Formal Description of Processes

A total of 9 papers (27.3%) could be assigned to the cluster of 'metamodels fostering the coherent formal description of processes'. These studies are addressing the need for a framework providing standards and reference models for the description and planning of processes.

Kathrein et al. (2019) develop an extension to the existing formal process description to model dependencies between product, production process, and production resources. Based on well-known standards and approaches like UML and BPMN a formal metamodel is provided, offering a structure and rule set for designing product, process, and resource details. To achieve coordination and consistency in the modeling of systems engineering key concepts, Jakjoud et al. (2016) introduce a unified system process engineering metamodel, a modeling language. A static description of the different components of systems engineering processes is given in the proposed metamodel. Further, Brunoe et al. (2019), Richter et al. (2016), and Karagiannis (2018) introduce formal metamodels to facilitate the initial process development phase.

The beforementioned research studies deal with ontology-based approaches of metamodeling, whereas Elfaham and Epple (2020) present a graph model displaying the topology of logistic networks in a given plant. The approach addresses the analysis of possible flow paths and the planning of respective transportation and process service sequences.

3.2.2 Metamodels Describing Process Information Exchange

A total of 7 papers (21.2%) could be assigned to the cluster of 'metamodels describing process information exchange'. Manufacturing processes and the interrelation between them and their support processes are complex and diverse. The papers in this cluster are dealing with the topic of structured description and modeling of the manufacturing process information. The proposed approaches can support process planning and facilitate information exchange.

Hildebrandt et al. (2017) and Vlasenko (2019) are describing the use of semantic metamodels to enable the modeling of information in the production domain. These models support the information exchange between different systems. Hildebrandt et al. (2017) outline the potential of using a metamodel for establishing a common understanding of information and thus, creating a basis for collaboration. To address the same issue, Yang et al. (2018) introduce a systematic and standardized modeling framework. The proposed metamodel is beneficial for standardized expression and improves the accuracy of manufacturing process information modeling. Furthermore, Lock and Reinhart (2016) define the concept of a metamodel to formalize interrelations between business processes and analyze influences within a process system. Therefore, different types of impacts are defined and used as a reference.

3.2.3 Supporting Decision-making through Metamodel-based Analysis

A total of 7 papers (21.2%) could be assigned to the cluster of 'supporting decision-making through metamodel-based analysis'. The related studies aim to introduce models to investigate relationships between input parameters and output variables of manufacturing processes, generating information, and insight into the production performance. This could be used to enables more accurate decision-making.

Salama and Eltawil (2018) introduce an approach for extending a decision support system for planning and operational control of cyber-physical production facilities. The authors use a simulation metamodel to gain insight into the system performance under various settings. Similarly, Lara et al. (2019) investigate different scenarios in reverse logistics for decision support. For this purpose and to ensure uniformity, the authors develop a metamodel that serves as a domain-specific modeling language. Moreover, Lara et al. (2020) and Utz and Falcioni (2018) introduce semantic metamodels to improve consistency in decision-making.

3.2.4 Metamodels Facilitating the Simulation of Manufacturing Systems

A total of 6 papers (18.2%) could be assigned to the cluster of 'metamodels facilitating the simulation of manufacturing systems'. With the increasing complexity of manufacturing systems due to rising demands for flexibility and customization, it becomes a crucial task to develop solutions to simulate this increasing complexity in manufacturing systems. The reviewed studies show approaches to define semantic metamodels and simulation frameworks to support the extraction of simulation sequences from physical manufacturing processes.

Merschak et al. (2018) demonstrate the use of a methodical framework to define the topology of a system and the interconnections between its subsystems. While Brovkina and Riedel (2019) conceptualize a semantic metamodel describing the structure, functions, and behavior of the components of a cyber-physical production system (CPS). The skill descriptions in combination with the appropriate manufacturing process description allow automatic matching for production planning. Moreover, Werke et al. (2015) present an algorithm for defining metamodels of

manufacturing sequences applying upstream search. This improves finding interconnected models. Applying these approaches in an early design phase can increase the efficiency in setting up the simulation system.

3.2.5 Establishing Modular Material Flow Systems using Metamodels

A total of 4 papers (12.1%) could be assigned to the cluster of 'establishing modular material flow systems using metamodels'. These research studies introduce modular concepts to improve interchangeability, interoperability, and consistency in automated material flow systems.

To improve the transferability and consistency of the information flow between engineering stages Regulin et al. (2016), as well as Aicher et al. (2016), introduce a modular architecture to maintain the flexibility and robustness of automated material flow systems. The proposed metamodel consists of subclasses, that address the requirements for the description of the material flow system. This ensures a thorough view of the modules of the automated material flow system, e.g., sensors and actuators. Based on the metamodel the effort to collect information shared over distinct domains in the stages of plant planning can be reduced. Further, decentralized and centralized control applications are enabled via consistent interfaces between the different modules. Brandenbourger et al. (2017) design a metamodel to enable coherent engineering between automation component manufacturers and plant-manufacturers. The metamodel holds generic information for automation components and thus enables the interchangeability of modeled components.

4. Discussion

The application of metamodels in manufacturing processes could be divided into five research directions. The mainly addressed issue is metamodeling as an approach to achieve uniformity, standardization, and coherent formal description of processes. For this purpose, the literature introduces semantic metamodels. The standardized language enhances interoperability not only between different stages of production but also between entities along the supply chain. In terms of ongoing digitalization and Industry 4.0, connected factories are evolving, therefore predefined standards play a key role to enable collaboration between them. The benefits of introducing semantic metamodels are also discussed in the fields of modeling process information exchange, in the design phase of manufacturing systems, and for ensuring consistency in decision-making.

The larger share of publications deals with the concept of metamodeling to provide a unified modeling language to allow better model creation and facilitate the mapping of connections between the subsystems and underlying information flows. One of the main practical applications is its usage in the planning and control of cyber-physical production systems.

To a lesser extent, the topic of metamodels for simulation modeling is dealt with in the presented research studies. With emerging complexity in manufacturing systems, a crucial future task will be the assessment and simulation of this complexity and the dynamics of the autonomous behavior of its elements. A few research studies elucidate the trend of simulation metamodeling to reduce the complexity of the system. Thereby, aggregated effects of process steps can be made visible, process parameters can be optimized and impacts of changes in the process steps can be evaluated.

Based on the findings of the structured literature review, a lack of research studies dealing with the introduction of graph-based metamodels to facilitate model creation can be identified. Further limitations of the current research work can be seen in the limited practical application of the presented approaches. The reviewed studies mainly address specific sectors, such as the control of cyber-physical production systems.

However, further research should be done on building a graph-based metamodel to describe interconnections between subsystems of the manufacturing system, to reduce its complexity, and facilitate model creation and evaluation.

5. Conclusion

In this paper, a structured literature review was conducted to show application areas for metamodeling approaches in manufacturing systems. Five research directions were defined and the use of semantic metamodels for standardization in process description, decision-making, information exchange, and in the design phase of manufacturing systems was identified.

Furthermore, a lack of studies on graph-based metamodels for simulation modeling was outlined. Also, the concept of metamodeling may be extended to fit a range of industry sectors to allow broader usage of the conceptualized frameworks.

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