Knowledge Graphs for the Enhancement of Process Planning in Manufacturing

Jonathan Reif, Tom Jeleniewski, Felix Gehlhoff
Institute for Automation Technology
Helmut Schmidt University/
University of the Federal Armed Forces Hamburg
Hamburg, Deutschland
{jonathan.reif, tom.jeleniewski, felix.gehlhoff}@hsu-hh.de

Alexander Fay
Chair of Automation
Ruhr University Bochum
Bochum, Deutschland
alexander.fay@rub.de

Constantin Hildebrandt
CTC GmbH (An Airbus Company)
Stade, Deutschland
constantin.hildebrandt@airbus.com

***Abstract*—The increasing complexity of modern manufacturing systems, driven by demands for sustainability, shorter product life cycles, and greater customization, necessitates frequent reconfiguration and redesign of production processes. In this context, knowledge about parameter interdependencies is crucial. Additionally, simulations play a vital role by enabling virtual testing of various parameter configurations to optimize key performance indicators such as energy consumption, emissions, processing time, and costs.**

This project report presents an integrated approach to enhance process planning by incorporating semantic models that describe process parameter interdependencies. Furthermore, we describe a concept for automating the generation of simulation sequences, thereby reducing the complexity and effort involved in manual planning. The combination of these approaches is demonstrated using a web-based application, showcasing the potential to support efficient and sustainable manufacturing practices.

***Index Terms*—Semantic Web, Simulation, Parameter Interdependencies**

I. Introduction

Due to a rising demand for customized products and a consequent reduction in lot sizes, contemporary production systems are becoming increasingly complex [1]. Additionally, manufacturing companies encounter significant challenges due to the wide range of possible configurations in production systems [2]. Current efforts to enhance sustainability and reduce emissions, energy consumption, and waste require considering various parameters and indicators in process design. However, only a limited number of experts possess in-depth knowledge about a production system or specific subareas, as such expertise is often confined to particular process steps.

A thorough and comprehensible documentation of the production system is essential for disseminating this knowledge to other stakeholders within a manufacturing company [3]. One critical area where this understanding is crucial is in the (re)design of production processes. Knowledge about the fundamental behavior of processes, the impact of parameter variations, and the effects of process changes (e.g., different raw materials) is essential. Complex production processes, particularly those with high unit costs, are often prohibitively expensive to conduct iteratively during the design phase [4]. Simulation provides a method for enhancing process knowledge virtually and allows for testing various parameter configurations in a cost-effective and timely manner [5]. However, selecting and planning these simulations is not trivial. Therefore, it is necessary to also store knowledge about available simulations in a semantic model to support their use.

An increasingly important approach for storing knowledge in a machine-readable form is the use of *Semantic Web* technologies, particularly ontologies. An ontology is defined as a ”formal, explicit specification of a shared conceptualization” [6]. The *SPARQL Protocol and RDF Query Language* (SPARQL) can be utilized to retrieve knowledge stored in an ontology. Semantic Web technologies have proven useful and are employed, for instance, as information models in manufacturing [3]. This project report aims to describe the application potentials of Semantic Web technologies in the context of process (re)design and to demonstrate practical suitability through a web-based demonstrator that implements various concepts for describing known parameter influences and supporting the simulation of such process information.

The background is introduced in Section II, followed by an explanation of the developed concept in Section III. Section IV describes the implementation of the concept in a prototypical demonstrator. Finally, Section V provides the conclusion and outlines future work.

II. Background

As outlined by Gill et al. [7], semantic web technologies present extensive opportunities for application in the manufacturing domain. These technologies enable the seamless integration of diverse models — structural, functional, and behavioral — by providing clear semantics, which ensure that design data can be effectively reused in subsequent lifecycle phases such as manufacturing and maintenance. This possibility enhances overall efficiency. [7]

Semantic technologies facilitate the formalization and integration of expert knowledge and decentralized data, which is crucial for understanding and managing process parameter interdependencies. By using ontologies, these technologies allow for the precise specification of process parameters and their interrelations, providing a comprehensive framework for documenting and retrieving process knowledge.

In the context of simulation support, semantic technologies can support the automated selection and planning of simulation sequences by enabling a comprehensive description of simulation resources, including input and output parameters, as well as other important properties. This supports virtual testing and optimization of manufacturing processes without the need for physical prototypes, thereby reducing costs and development time while maintaining high-quality production outcomes. The integration of simulations with semantic models allows for the automated planning of simulation sequences, ensuring that the most appropriate simulations are selected and executed based on defined criteria and interdependencies.

In summary, semantic technologies offer a robust framework for integrating and managing digital artifacts in manufacturing. They address data interoperability challenges and enable more efficient and effective lifecycle management, particularly in the areas of process (re)design, parameter interdependency analysis, and simulation support.

III. Concept

Based on the identification of individual application potentials as described by Gill et al. [7], a comprehensive concept to leverage these potentials was developed. The primary objective of this concept is to address user queries. These queries relate to various process variables that arise from executing the process with specific parameters.

The concept aims to support users in the context of process (re)design by providing information about process parameter interdependencies or, when necessary, facilitating the virtual generation of this information through simulations. To address user queries, different methods complementing each other, each accompanied by its own developed concept, were identified.

If the process has already been executed with the parameters for which the user seeks process variables, the query can be answered using historical process data. Otherwise, the required knowledge can be derived from functional interdependencies or generated via simulations.

The core of the concept is a knowledge model in the form of an ontology. This approach ensures that the concept remains as generic as possible. By exchanging the application-specific ABox in the knowledge model, the concept can be applied to other use cases or processes while the structure of the knowledge model (TBox) remains. The knowledge model integrates both, machine data and expert knowledge.

In this section, we present the sub-concepts *Process Knowledge Retrieval, Historical Process Data, Parameter Interdependency Description and Simulation Support* before demonstrating their combined use in a web application in Section IV. The sub-concepts and their interaction are illustrated in Figure 1.

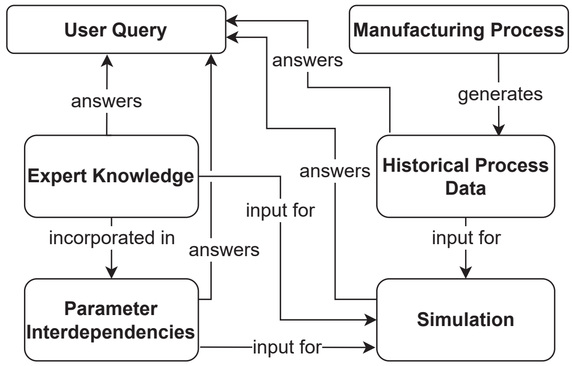

Figure 1: Presented sub-concepts and their interactions

A. Process Knowledge Retrieval

An ontology includes not only a conceptual vocabulary but also precise definitions for each term, delineating the relation among concepts. The methodological framework detailed by Hildebrandt et al. [3] was used for developing the ontology. This framework is designed for the structured development of ontologies within manufacturing environments and was applied during workshops with project partners.

To enhance generalizability and standardization while reducing modeling effort, *Ontology Design Patterns* (ODPs) are utilized. These patterns provide modeling solutions for recurring problems in ontology design [8]. Unlike an ontology developed from scratch, this approach allows for high reusability of previous models, ensuring that developments in this research area can be reused in other applications. These ODPs are maintained separately and imported into an alignment ontology, facilitating the integration of additional standards and ODPs as needed [3].

Following the requirement analysis, ODPs based on industrial standards and containing the necessary terminologies for the application were identified. For instance, the ODP based on the VDI/VDE 3682 guideline for Formalized Process Description was implemented in the concept to address recurring issues in describing discrete or continuous production processes [9]. To ensure compliance with these guidelines during modeling, a web-based modeling tool, introduced by Nabizada et al. [10] following VDI/VDE 3682, was used. A mapping feature enables automated conversion of process descriptions from the modeling tool's export format into an ontology.

To specify additional information or data, such as process parameters, the DIN EN 61360 standard [11] and its corresponding ODP are used, which allow detailed descriptions of data elements with associated types and instances. For data element type descriptions, unit specification is limited to freely selectable strings. However, it is crucial to define terminologies for standardized units, so an additional ODP containing the UNECE-recommended classification of measurement units is included. The proposed model also uses this ODP to assign standardized units to type definitions. A particular focus is placed on the relations between equipment, processes, and products, as well as on the specification of related process parameters. However, the process description alone cannot adequately represent the extent to which input parameters influence specific output variables or the impact of changes in input variables. This underscores the necessity to expand the ontology with additional concepts and terminologies.

B. Historical Process Data

In the context of manufacturing processes, systematic collection and storage of various machine data are performed. The recording and documentation of all events, state changes, and process steps enable the creation of a comprehensive process history. To effectively utilize these data, it is essential to embed them within a contextual framework that allows user-oriented insights and interpretations.

A key element in this process and the overall concept is linking the machine data to an ontology. This linkage enables the interpretation of data concerning their semantic meaning and context, focusing on the virtualization approach.

By making historical data available in the ontology and enriching it with a semantic meaning there is the possibility to utilize this data in the concept to answer user queries.

C. Parameter Interdependency Description

In the proposed concept, it is essential to clearly articulate the known interdependencies between parameters, especially when assessing the impacts of process changes. The process ontology described in Section III-A has been extended by Jeleniewski et al. [12] to facilitate the representation of process parameters and their interdependencies. A class diagram of the developed ontology is shown in Figure 2.

In this model, concepts from the *Formalized Process Description* (FPD) as outlined in the guideline *VDI/VDE 3682* [13] are incorporated. Furthermore, the ODP from the *DINEN 61360* standard [14], which includes a framework for specifying data elements with types and instance descriptions, is used for modeling process parameters. Restrictions can also be applied to these parameters, as demonstrated by Jeleniewski et al. [15]. To add unit of measurement information to the data elements, type descriptions are additionally classified using a *UNECE* unit of measurement class [16].

Additionally, the model integrates the OpenMath ontology, as presented by Wenzel [17], which enables the representation of mathematical expressions and functions. These mathematical expressions are correlated in the model with the process description elements of *VDI/VDE 3682* and their corresponding data elements to formally describe interdependencies among process parameters.

One advantage of the FPD is the ability to model at various levels of abstraction, allowing for both detailed and generalized process representations as needed. Jeleniewski et al. [15] propose a method to unify the concepts of composition and decomposition from both mathematical and process description perspectives, linking decomposable process operators with descriptive functions. Since interdependency descriptions are directly associated with a process operator, this methodology supports the decomposition and composition of process operators and their corresponding mathematical expressions

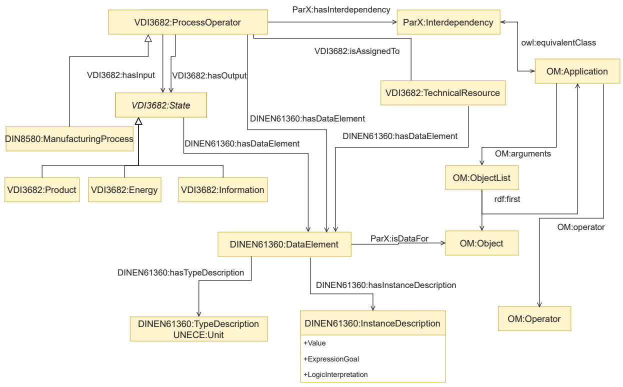

Figure 2: Class diagram of the Parameter Interdependency Ontology (ParX) based on [19]

for describing interdependencies. However, this flexibility can complicate the integration of mathematical expressions for interdependency descriptions.

To address this challenge, Jeleniewski et al. [18] have developed a structured method for integrating interdependencies. Additionally, Jeleniewski et al. [12] provide an extensive modeling and querying example using SPARQL. A method to enhance the SPARQL queries with a data consistency check, ensuring the return of correct process-related data along with the corresponding mathematical expressions, is detailed in Jeleniewski et al. [15].

D. Simulation Support

As outlined in I, simulations play a crucial role in analyzing manufacturing processes. They can depict various elements of the production process and related systems, facilitating the virtual generation of process information and enabling cost-effective testing of different process parameter configurations within reasonable time frames [5].

However, a single simulation often is not able to provide a complete understanding of specific process settings. Instead, multiple simulations are needed, where the outputs of one serve as inputs for another, forming a sequence of simulations. Moreover, simulations of the same object of consideration, e.g. the same process step, are often available at different complexity levels, necessitating a selection based on time and resource constraints. The general approach is to simulate most of the system at the lowest complexity and only simulate specific parts in more detail when necessary [20].

Due to these factors, manually creating simulation sequences is complex, time-consuming, and prone to errors. It requires in-depth knowledge of simulations, their parameters, and the entire production process. To automate the creation of simulation sequences, a machine-interpretable model is essential. This model must describe simulations, their functionalities, and relevant properties.

This model forms the basis for the method introduced by Reif et al. [21] for planning simulation sequences, enabling the

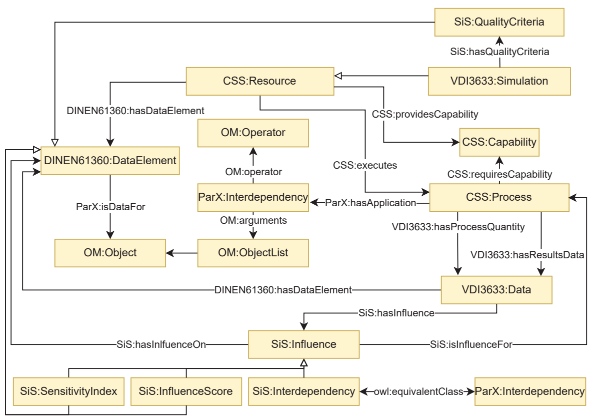

Figure 3: Components of the *Simulation Support* (SiS) ontology [24]

selection and planning of simulations. A class diagram of the model, which was implemented as an ontology is illustrated in Figure 3.

The model integrates the industrial standard VDI 3633 [22] to outline various simulations along with their input and output parameters. Additionally, it employs the *Capability-Skill-Service* (CSS) model [23] to describe the capabilities of these simulations. In the CSS context, capabilities are abstract descriptions of functions required by processes and provided by resources [23]. This capability description within the model enables the selection of simulations based on their ability to generate specific process information. Furthermore, the model also utilizes the *DINEN 61360* standard [11] to model characteristics of parameters.

Moreover, the model incorporates quality criteria to assist in choosing simulations that are more suitable for particular use cases. The description of the influence of parameters is critical in this selection process. If an input parameter significantly influences the output of a simulation, it should receive more consideration during the selection process, or in the context of simulation sequences, the simulation generating this input parameter should be prioritized over others with negligible influence on the output. The model provides three methods to describe these parameter influences, one of which utilizes the *Parameter Interdependency* (ParX) ontology [19] to depict parameter influences in the form of mathematical functions. Other types of influences are expressed as an index resulting from sensitivity analysis or as a score resulting from expert knowledge.

IV. Production Ontology Demonstrator

The combination of the concepts described in Section III was implemented in a demonstrator to showcase their potential and usability in an industrial setting. This demonstrator enables experts from various domains to explore approaches for knowledge description, discovery, retrieval, and generation. The primary goals are to demonstrate the potential of these technologies, encourage professional discussions, and align research approaches with industrial needs.

During the development of the demonstrator, significant focus was placed on understanding the interactions between various parameters and their effects on both the process and its output variables. Given the high costs and time associated with real production processes, there is a strong interest in obtaining process knowledge, particularly about the influence of different input parameters on outputs, without physical execution. This approach allows for testing different process variants with varying parameters.

Initial solutions to these challenges were implemented in the presented demonstrator. The various functions implemented in the demonstrator are shown on *YouTube* [1]. It can query various aspects of the knowledge model, including process descriptions based on the product-process-resource approach according to the FPD and associated information or process parameters. These parameters are enriched with information about attributes, units of measure, and additional information such as influences and restrictions (upper and lower limits). Simple physical relations were also modeled in graph form and made available for querying. Additionally, the demonstrator supports users through a graphical interface to create, visualize, and delete knowledge.

Furthermore, process information can be generated through prototypical simulations connected to the demonstrator. Users can input various process parameters via a flexible user interface to query whether historical process information exists for the respective parameter combinations and select simulations to generate missing process information.

It is also possible to execute selected simulations with the input parameters, thereby generating new process information. Due to the combination of process models including the description of interdependencies and the simulation models, process information can also support the execution of simulations. For example, production restrictions contained in the process model can simultaneously restrict the input of parameters in the simulation. Other benefits of linking the information models include connecting real process parameters with simulated process parameters. This linkage allows for diverse input sources for simulation input parameters, such as historical data or process interdependencies. Additionally, it facilitates the simulation of missing process information or the derivation of information through functional parameter interdependencies.

Similar to the knowledge model, the development of the demonstrator emphasized generalizability and transferability to other processes through ontology-based approaches.

The demonstrator, described in this section, was developed as a web application using *Angular*[2] for the frontend and *NestJS*[3] for the backend. As shown in Figure 4, the user interacts with the frontend interface, which triggers HTTP requests

[1] https://www.youtube.com/watch?v=Jt39YbPkwVk
[2] https://angular.dev/
[3] https://nestjs.com/

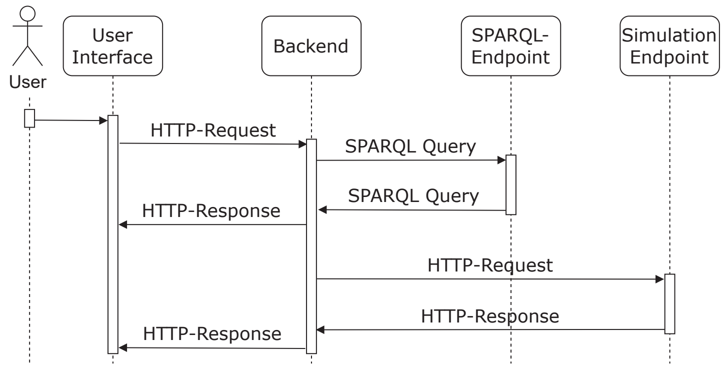

Figure 4: Sequence diagram of the production ontology demonstrator

to the backend. The backend communicates with a SPARQL endpoint, implemented in a graph database via SPARQL queries. Similarly, users can interact with the Simulation-Endpoint by triggering HTTP requests to the backend through the frontend, executing simulations in the functional mockup unit format connected to the demonstrator via a web interface. This allows users to generate required process information.

The demonstrator is designed so that users do not have to interact directly with the ontology via SPARQL, but are supported by an intuitive user interface for every action. This ensures that the created information model is accessible not only to ontology experts but also to other stakeholders in a manufacturing company.

V. Conclusion and Future Work

This project report describes an approach to enhancing process planning in manufacturing by integrating semantic models and simulations. By leveraging knowledge about process parameter interdependencies and supporting the selection and planning of simulation sequences, the proposed concept offers ways to improve efficiency and sustainability in manufacturing systems.

The developed ontology-based knowledge model facilitates the representation of complex manufacturing processes and their interdependencies, allowing for better documentation, retrieval, and application of process knowledge. This is particularly valuable given the increasing demands for customization and sustainability in manufacturing. The concept of linking historical process data with semantic models further enriches the knowledge base, enabling more informed decision-making.

The demonstrator highlights the practical potential of these concepts, offering a user-friendly interface for querying and generating process information. This tool supports users in both retrieving existing knowledge and generating new knowledge through simulations.

Future work will focus on expanding the scope and functionality of the demonstrator. This includes incorporating more advanced simulation capabilities, improving the integration of real-time data, and enhancing the user interface to support a wider range of industrial applications. Additionally, efforts will be made to further standardize the knowledge models, promoting broader adoption and interoperability across different manufacturing systems.

Moreover, research will continue to refine the automated planning of simulation sequences, exploring more sophisticated algorithms and techniques to optimize the selection and execution of simulations. These advancements aim to further reduce the complexity and effort required in manual process planning, ultimately driving greater efficiency and sustainability in manufacturing practices.

In conclusion, the integration of Semantic Web Technologies and simulations represents a promising direction for the future of process planning in manufacturing. By harnessing the power of knowledge graphs and simulation, this approach provides a robust framework for addressing the challenges of modern manufacturing, paving the way for more efficient, sustainable, and customizable production processes.

Acknowledgment

This project report [project LaiLa] is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge. dtec.bw is funded by the European Union – NextGenerationEU.

References

[1] P. Leitão, “Agent-based distributed manufacturing control: A state-of-the-art survey,” *Engineering Applications of Artificial Intelligence*, vol. 22, no. 7, pp. 979–991, 2009.
[2] M. Garetti, L. Fumagalli, and E. Negri, “Role of Ontologies for CPS Implementation in Manufacturing,” *Management and Production Engineering Review*, vol. 6, no. 4, pp. 26–32, 2015.
[3] C. Hildebrandt, A. Köcher, C. Küstner, C.-M. Lopez-Enriquez, A. W. Müller, B. Caesar, C. S. Gundlach, and A. Fay, “Ontology Building for Cyber–Physical Systems: Application in the Manufacturing Domain,” *IEEE Transactions on Automation Science and Engineering*, vol. 17, no. 3, pp. 1266–1282, 2020.
[4] S. N. Grigoriev, A. A. Kutin, and M. V. Turkin, “Modelling Complex Production Processes in Aerospace Industry based on Dimensional Analysis,” *Procedia CIRP*, vol. 7, pp. 473–478, 2013.
[5] D. Mourtzis, “Simulation in the design and operation of manufacturing systems: state of the art and new trends,” *International Journal of Production Research*, vol. 58, no. 7, pp. 1927–1949, 2020.
[6] R. Studer, V. Benjamins, and D. Fensel, “Knowledge engineering: Principles and methods,” *Data & Knowledge Engineering*, vol. 25, no. 1-2, pp. 161–197, 1998.

[7] M. S. Gill, J. Reif, T. Jeleniewski, M. Weigand, and A. Fay, "Application potentials of Semantic Technologies for Digital Twins in Aircraft Design, Manufacturing and Maintenance."

[8] A. Gangemi and V. Presutti, "Ontology Design Patterns," in *Handbook on Ontologies*, S. Staab and R. Studer, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 221–243.

[9] VDI, "Richtlinie VDI/VDE 3682: Formalisierte Prozessbeschreibungen," Mai 2015.

[10] H. Nabizada, A. Köcher, C. Hildebrandt, and A. Fay, "Offenes, webbasiertes Werkzeug zur Informationsmodellierung mit Formalisierter Prozessbeschreibung," in *Automation 2020*. VDI Verlag, 2020, pp. 443–454.

[11] DIN EN 61360-1, "Standard data element types with associated classification scheme - Part 1: Definitions - Principles and methods (IEC 61360-1:2017)," 07.2018.

[12] T. Jeleniewski, H. Nabizada, J. Reif, A. Köcher, and A. Fay, "A Semantic Model to Express Process Parameters and their Interdependencies in Manufacturing," in *2023 IEEE 32nd International Symposium on Industrial Electronics (ISIE)*. IEEE, 2023, pp. 1–6.

[13] VDI/VDE 3682:1, "Formalised Process Descriptions - Concept and Graphic Representation," 2015.

[14] DIN EN 61360-1, "Standard data element types with associated classification scheme - Part 1: Definitions - Principles and methods (IEC 61360-1:2017)," 2018.

[15] T. Jeleniewski, J. Reif, F. Gehlhoff, and A. Fay, "Parameter Interdependencies in Knowledge Graphs for Manufacturing Processes," in *2024 IEEE 29th International Conference on Emerging Technologies and Factory Automation (ETFA)*. IEEE, 2024, pp. 1–8.

[16] UNECE, "Recommendation No. 20: Codes for Units of Measure Used in International Trade," 2010.

[17] K. Wenzel, "OpenMath-RDF: RDF encodings for OpenMath objects and Content Dictionaries," in *31st OpenMath Workshop*, 2021.

[18] T. Jeleniewski, J. Reif, and A. Fay, "Integrating Interdependencies in Semantic Manufacturing Process Description Models," in *2023 IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA)*. IEEE, 2023, pp. 1–4.

[19] T. Jeleniewski, H. Nabizada, J. Reif, A. Köcher, and A. Fay, "A Semantic Model to Express Process Parameters and their Interdependencies in Manufacturing," in *2023 IEEE 32nd ISIE*. IEEE, 2023, pp. 1–6.

[20] P. Puntel-Schmidt and A. Fay, "Levels of Detail and Appropriate Model Types for Virtual Commissioning in Manufacturing Engineering," *IFAC-PapersOnLine*, vol. 48, no. 1, pp. 922–927, 2015.

[21] J. Reif, T. Jeleniewski, and A. Fay, "An Approach to Automating the Generation of Process Simulation Sequences," in *2023 IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA)*. IEEE, 2023, pp. 1–4.

[22] VDI 3633:1, "Simulation of systems in materials handling, logistics and production," 12.2014.

[23] A. Köcher, A. Belyaev, J. Hermann, J. Bock, K. Meixner, M. Volkmann, M. Winter, P. Zimmermann, S. Grimm, and C. Diedrich, "A reference model for common understanding of capabilities and skills in manufacturing," *at - Automatisierungstechnik*, vol. 71, no. 2, pp. 94–104, 2023.

[24] J. Reif, T. Jeleniewski, A. Köcher, T. Frerich, F. Gehlhoff, and A. Fay, "Semantic Capability Model for the Simulation of Manufacturing Processes," in *Proceedings of the 16th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management*. SCITEPRESS - Science and Technology Publications, 2024.