Proceedings of the 2025 Winter Simulation Conference
E. Azar, A. Djanatliev, A. Harper, C. Kogler, V. Ramamohan, A. Anagnostou, and S. J. E. Taylor, eds.

ANALYZING IMPLEMENTATION FOR DIGITAL TWINS: IMPLICATIONS FOR A PROCESS MODEL

Annika Hesse[1] and Hendrik van der Valk[1,2]

[1]Chair of Industrial Information Management, TU Dortmund University, Dortmund, GERMANY
[2]Fraunhofer Institute for Software and Systems Engineering, Dortmund, GERMANY

ABSTRACT

For many companies, digital transformation is an important lever for adapting their work and business processes to constant change, keeping them up-to-date and reactive to changes in the global market. Digital twins are seen as a promising means of holistically transforming production systems and value chains, but despite their potential, there has been a lack of standardized implementation processes, often resulting in efficiency losses. Therefore, this paper aims to empirically identify process models for implementing digital twins through a structured literature review and derive implications for a standardized, widely applicable process model. The literature review is based on vom Brocke's methodology and focuses on scientific articles from the last years. Based on 211 identified publications, relevant papers were analyzed after applying defined exclusion criteria. The results provide fundamental insights into currently used process models and open perspectives for developing a standardized implementation framework for digital twins.

1 INTRODUCTION

Many companies are currently facing the challenge of adapting their work and business processes to constant change, keeping them up to date, and at the same time being able to react flexibly to changes in the global market (Brassey et al. 2024). An important guarantor of this is digital transformation, which enables the digitalization and virtualization of business and work processes (Herberger and Dötsch 2021). Although the digital transformation in the context of Industry 4.0 started over a decade ago, many companies are still relatively at the beginning of a development and implementation cycle (Ritter and Sobania 2024). Their business areas have simply not yet been transformed.

Digital twins are one option for the holistic transformation of production systems, logistics networks, or entire value chains (van der Valk et al. 2024). As an image of a physical object, they make it possible to animate such systems while simultaneously recording and evaluating data (Tao et al. 2019). In this way, analyses and improvements to existing systems can be carried out at any level of complexity. The market launch of digital twins is relatively new (Grieves 2023). At the same time, however, many individual approaches to implementing digital twins exist. However, most of this implementation does not follow standardized procedures but, as usual with young digital entities, is subject to pragmatic approaches (van der Valk et al. 2024). It has already been shown in the past that unstructured approaches to implementing digital entities such as the Internet of Things, Big Data technologies, and automation processes in general within Industry 4.0 negate many efficiency gains and potential savings from the outset. It is, therefore, all the more important to use a standardized framework for implementing digital twins. Due to the relatively recent history of digital twins, it is still possible to define such a framework and roll it out widely as an industry standard. The first efforts in this direction already exist but are not yet ready for widespread use. However, it is possible to analyze these initial approaches and derive guidelines regarding a best practice approach.

Thus, our research objectives (RO) read as follows:

RO1: Obtain empirical process models based on a structured literature review.

The first RO lays the foundation for further analysis. With empirical data from process models used only in singular cases, a best practice approach may be derivable. Therefore, the second RO is:

RO2: Derive implications for the design of a standardized and, thus, broadly applicable process model.

Here, we take the leap from the descriptive analysis and provide insights and the foundation for a more detailed design of a process model that not only fits one case but a multitude of cases in different domains. With a standardized process model, we define a process model that makes use of standards in any form. These can be modeling languages such as UML, semantical or syntactical standards, or standards for process management.

The paper is structured accordingly to achieve the objectives. First, we will shed light on the foundations of digital twins and process models in information systems. We explain our research approach and the details of the structured literature review (SLR) in Section 3. The proceeding section deals with the application of process models during the digital twin implementation. We discuss interesting observations in Section 5 and provide an overview of implications for the process model design. We conclude the paper with a brief description of the contributions, limitations, and paths for further research.

2 THEORETICAL BACKGROUND

Digital twins represent a crucial technological frontier that connects the physical and digital worlds. While the field has progressed, and digital twins can now be found in various domains and use cases, it originated in the aerospace industry (Grieves 2023). Michael Grieves (2014) developed the digital twin concept as a virtual unit for product lifecycle management. However, in his collaboration with NASA, simulations of products, i.e., spacecraft and airplanes, quickly became an essential part of the digital twin (Shafto et al. 2010; Tuegel 2012). Over the years, the concept has been continuously refined and now consists of five central units (Tao et al. 2019; Tomczyk and van der Valk 2022). These are the physical object, the virtual image, the bi-directional data flow between virtual space and physical space, the integration of data flows and interfaces for other external units, and the internal services (Jones et al. 2020; Tao et al. 2019; van der Valk et al. 2022).

The digital twin is closely linked to the Internet of Things, especially in the production context (van der Valk et al. 2022). In the areas of healthcare, smart city, or biochemical technology, the digital twin is used for process monitoring and simulation (Canzoneri et al. 2021; Mohammadi and Taylor 2018; Strobel et al. 2022). Especially in recent times, the digital twin has often been enriched with properties of generative artificial intelligence and large-scale models (Schwede and Fischer 2024). Therefore, the aforementioned industries, i.e., production, logistics, mobility applications, and healthcare, are the ones benefiting the most from seamless digital twin implementations.

In many areas, digital twins are seen as a further development of classic simulation technology (Boschert and Rosen 2016). However, the digital twin combines the possibilities of simulation with data acquisition and data distribution in the context of data spaces, for example, the Asset Administration Shell, or as agents within larger data ecosystems (Lüder et al. 2020; Ryu et al. 2024). Unsurprisingly, simulation is deemed a core function of the digital twin, yet the twin enhances the simulation part and provides many more data processing and handling options (van der Valk et al. 2022).

The first standards, such as ISO 23247 or the reference architectures of the Industrial Digital Twin Association, exist for the digital twin (IDTA 2023; ISO 23247 2021). However, there are still some challenges. The field of digital twins in broad industrial use is relatively young and has only developed in the last five years. Naturally, this is a very diversified market with few general solutions (Fortune 2024). Although many digital twins are in a proof of concept or pilot phase, only a few are already in operation. As a result, there is still little experience in implementing and realizing digital twins for large projects (van der Valk et al. 2024).

Process models are utilized to create digital twins and provide clear guidelines to systematically support their development, enabling companies to use this technology in a targeted manner to increase the efficiency and reliability of products and systems (Göllner et al. 2023). Process models are understood as semi-formal, structured representations of the logical and temporal sequence of process steps and are considered the basis for implementing process-oriented approaches (Becker et al. 1997). They are valuable tools that facilitate the organization and control of developmental activities for new products (Cooper 1983). In addition to supporting development, they can also be used to define and document requirements (Figl et al. 2013). Typically, process models comprise graphical depictions of the modeled process-oriented approach's activities, events, and states (Recker et al. 2014).

3 RESEARCH METHOD

The present study aims to provide implications for process models based on findings in relevant literature. Therefore, we conducted a comprehensive SLR according to the methodological guidelines of vom Brocke et al. (2009). According to vom Brocke et al. (2009), an SLR is carried out in five steps: (1) definition of the review scope, (2) conceptualization of the topic, (3) literature search, (4) analysis of the literature, and (5) definition of the research agenda.

First, we define the scope of the literature research intended to answer the ROs. Therefore, the scope is defined as scientific publications that use process models to implement digital twins published in established scientific databases (SCOPUS, IEEE Xplore). These databases cover a wide range of relevant disciplines and ensure that both technical and interdisciplinary contributions can be identified. The two aspects of the process model and the digital twin need to be considered in more detail to conceptualize the topic. To define the term "digital twin" more precisely, we use the definition of van der Valk et al. (2022), who describe a digital twin as follows: "The Digital Twin is a virtual construct that represents a physical counterpart, integrates several data inputs with the aim of data handling and processing, and provides a bi-directional data linkage between the virtual world and the physical one. Synchronization is crucial to the Digital Twin to display any changes in the state of the physical object." Moreover, the search was restricted to the last three years as the definition of the digital twin has evolved. Consequently, the objective was to include only current publications that reflect this new understanding. To gain insight into the full range of process models in use, it is impossible to specify a limited number of standardized ones. In the third step, the literature search provided 211 papers with the search string ("digital twin" AND "process model") applied to the title, abstract, and keywords (see Figure 1).

After collecting possible scientific publications, we comprehensively analyzed the literature in the fourth step and filtered it using various exclusion criteria. The initial selection comprised all papers, which were only the proceedings descriptions. These are not separate research units but a collection of individual papers that we analyze. In the second step, we excluded all duplicate papers. Therefore, the hits from IEEE Xplore are compared with the ones from Scopus. The next selection criteria comprised all papers that were not readily accessible and had not yet been published.

Additionally, in this step, we excluded papers according to the quality criteria proposed by vom Brocke et al. (2009), such as that the publication must be methodically consistent and comprehensible. We analyze the remaining 132 papers. In order to respond to the RO, the thematic focus of the paper should be on digital twins and process models rather than merely mentioning them in passing. Consequently, we excluded all papers in which no digital twin is discussed according to the underlying definition, or the process model used cannot be clearly assigned. Following the application of all exclusion criteria, we identified a total of 38 papers as relevant (see Figure 1). These papers were analyzed in terms of different aspects. First, we look at bibliographic information such as the year, the country of origin, the chosen form of publication, whether the article is a journal or a conference paper, and in which domain the digital twin and process model are recognized. Second, we analyze which standardized or self-developed process model was implemented for the digital twin.

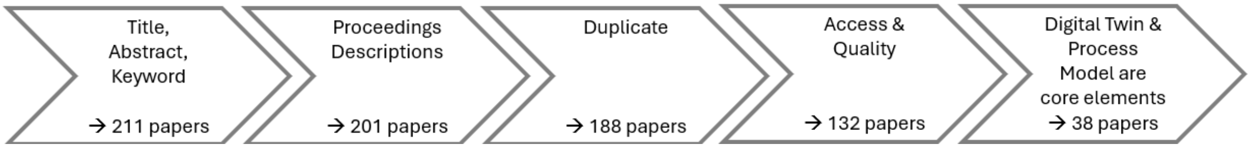

Figure 1: Systematic literature review process.

4 APPLICATIONS OF PROCESS FRAMEWORKS

We start our literature analysis with the demographic evaluation of the hits of the total of 188 papers found. Almost 30% of the papers are to be excluded due to quality deficiencies or the problem that they are not available for analysis (cf. Section 3 & Figure 2). We analyzed the remaining 70% with a full-text analysis. However, a further 30% of the papers were also sorted out because they were not relevant to the goal of the study, namely, process models for the implementation of digital twins. This shows a problem with the search term process models. This term is used not only for structured implementation but also by the processing and chemical industries for chemical and metallurgical processes.

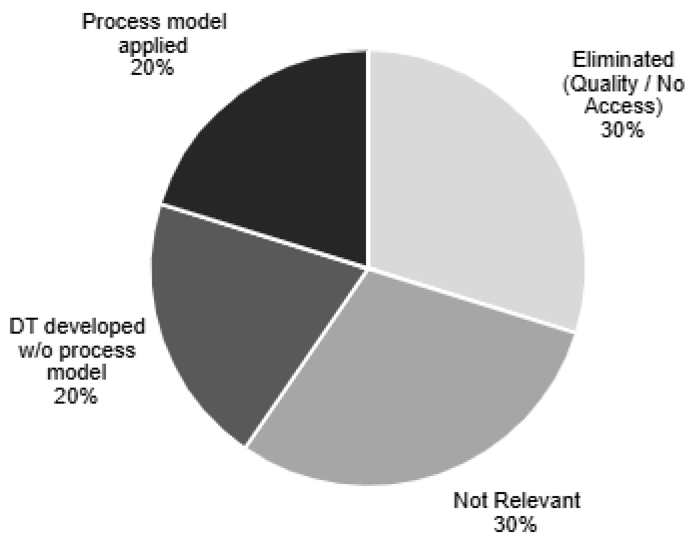

Figure 2: Distribution of the objects.

However, the remaining papers are very valuable for our further analysis. In order to have a current data status, we restricted the search to the last three years (cf. Section 3). The annual distribution of hits is chromogenic, however, and fluctuates between 32 and 34% in the years 2022 to 2024. Relatively few papers (just under 3%) are attributable to the year 2025, but this is because the data was recorded at the beginning of this year. A similar number of publications on this topic are expected in the course of the year 2025. The papers show an even distribution of geography. Therefore, we are able to include knowledge from various sources, e.g., Asia, Europe, and America.

Furthermore, the results are categorized into different domains based on content. The results fall into one of six different domains: Chemistry and Biotechnology, Construction, Energy, Information Technologies, Logistics, and Manufacturing. The Manufacturing domain accounts for 45% of the papers, making it by far the most represented domain. This underlines the central importance of this domain for the implementation of digital twins, especially in the context of digitalization, automation, and Industry 4.0. The domains Construction, Energy, and Logistics each account for 13% of the hits. The analysis reveals that 11% of the papers can be categorized within the domain of Logistics, while a mere 5% can be allocated to the domains of Chemistry and Biotechnology.

Finally, the hits found can also be categorized according to the number of journal articles and conference press releases. Slightly more than half (just under 55%) of the papers found appeared in journals, while the rest were published at conferences. This shows the relatively high maturity of the articles, as they are usually first published at conferences and then as second editions in journals.

In general, all applied process models belong to one of two meta-categories. These are allogenic approaches, i.e., openly regulated ones, and autogenously developed approaches. To the latter, we count proprietary process modeling, proprietary process modeling using Business Process Model and Notation (BPMN), and hierarchical process modeling. The former contains the remaining six categories: stochastic process modeling, Design Research Methodology, organizational standards, machine learning algorithms, workflow modeling, and process mining (cf. Figure 3).

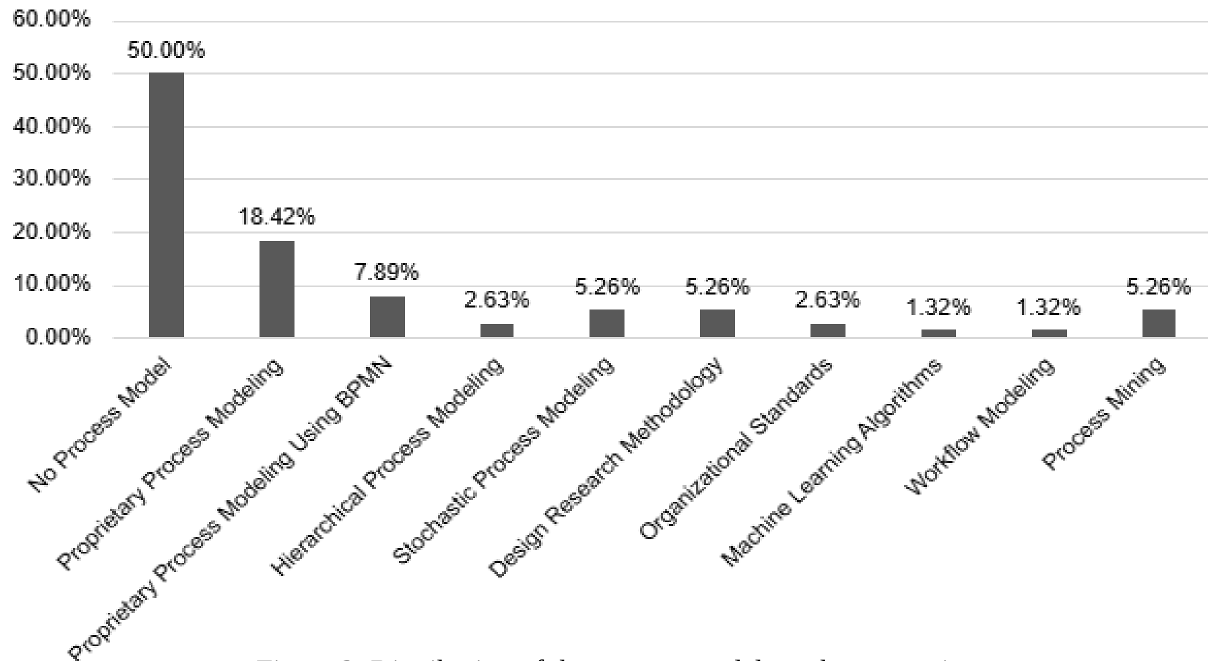

Figure 3: Distribution of the process models to the categories.

The proprietary process modeling comprises the majority of objects, with more than 36%. This category includes all process models, which, although they continue a structured procedure when implementing a digital twin, are simultaneously complete in-house developments of the corresponding authoring team. Thus, no super-organizational standards are used here. These process models are not necessarily counted on to be transferable to other use cases. This category is a kind of linking category between the majority of objects that do not describe any process models for implementing a digital twin and those that use standards and regulated approaches. With more than a third of the objects, this category is more than twice as large as the second-largest category. Examples of this include Kolditz et al. (2023), who execute a seven-step approach. For instance, they start with data integration and model generation, going through process simulation, system optimization, observation, and monitoring (Kolditz et al. 2023). Another example is Sarantinoudis et al. (2023). They derive a multi-step process model, especially focused on model generation and operation.

The next category is the proprietary process modeling using BPMN, which is also the second largest category. It contains process models that are also non-regulated but use BPMN. Analogous to the previous category, they reinforce the free process modeling once again. Yet, by adding BPMN, they provide a little more structure than the first category. BPMN is a graphical notation designed to map business processes in a workflow and provide a clear visual representation of step-by-step procedures and interactions within and between organizations (Ghasemi et al. 2024). BPMN is not merely a graphical notation but the de facto standard for business process modeling (Compagnucci et al. 2024). The notation is regarded as straightforward to utilize, familiar to most process modeling users, and features a widely adopted graphical representation (Da Torres et al. 2023). Göllner et al. (2023) apply BPMN for the designation of a procedure on how to act to prepare a company for a digital twin. For example, a workshop shall deliver a glossary and a clear definition. Furthermore, a use case is specified, and products with their interfaces are prioritized. Similarly, Mallek-Daclin et al. (2023) align the business processes with the implementation of a digital twin and, thus, provide a corresponding architecture.

The third category in the area of autogenous process models is the hierarchical process model, which accounts for just over 5% of the objects. An example of this is Schmidt et al. (2022), who provide an overview of the development and application of digital twins in continuous bioproduction based on validated process models. They show how digital twins contribute to optimizing and automating biotechnological processes by integrating real-time data, process analytical technology, and a fully-fledged model-based digital twin. The model contains the actions and steps necessary to transform the steady-state mathematical model into the digital twin. It reflects the general process of hierarchical steps required to transform digital models into digital twins.

Overall, the autogenous process models account for just under 58% of the objects and thus make up the majority of the objects.

The allogeneic approaches start with the stochastic process modeling. Nearly 10.5% of all objects fall into this category. With the stochastic approaches, for example, Li and Hu (2024) present a novel channel access control scheme for industrial Internet of Things systems called Digital Twin-based Parallel Learning and Optimization. They aim to make radio channel access decisions in industrial networks more efficient by combining digital twins and Markov decision processes (Li and Hu 2024). The Markov decision Process is a mathematical model in this paper that helps the system make smart decisions about channel access despite uncertainty in the environment. Another example is Sodachi et al. (2024), who use a Markov model.

Also, the design research methodology approaches are about the same size at 10.5%. Here, three further approaches are used. The first is the consortium approach, where a process model for creating a 3D factory layout is developed with the aim of converting previous 2D planning processes into 3D planning to create the basis for the digital factory twin (cf. Disselkamp et al. 2024). The model is broken down into six different steps that need to be taken. Secondly, the Design Science Research Method is a six-step approach that is particularly popular in modeling information systems (Peffers et al. 2007). The six steps of the design research lead from the initial question and problem definition via the domain description to the design of an artifact. The six steps of the design approach lead from the initial question and problem description to the design of an artifact, in this case, a digital twin. Yet, they also include the demonstration and evaluation of the same, and finally conclude with the communication (cf. Heininger et al. 2024). The third option of the design research approach is the so-called Action Design Research approach, which regularly switches back and forth between three levels and thus offers a close connection between theoretical knowledge, practice-oriented modeling, and practical implementation (Sein et al. 2011). In addition to the three levels, the requirements elicitation, artifact modeling, evaluation, and demonstration phases are also pursued here. Examples are Salinas Segura et al. (2024) or Salvi et al. (2022).

The next category is the organizational standards. This category only contains 5% of the objects. Nevertheless, it is an exciting category. In theory, one would assume the application of several frameworks that originate in organizational structures. For instance, the German Association of Engineers (VDI), the British Digital Twin Hub, and the International Organization for Standardization ISO publish many process models. Within the simulation community, the following process models are especially popular. First, there is the VDI 3633 (VDI 2014). This model prescribes a parallel structure in which the model is created from an initial definition of the objectives and tasks via conceptual and formal modeling, data preparation, and evaluation.

An example of organizational standards is provided by Kirchberger et al. (2022). They propose to use a process model for factory planning. Therefore, they apply an existing process model, which was originally used for an application case for digital twins and not for the twin itself. This shows two things. First, digital twins are so diverse that they may be implemented based on procedures for digital twins' applications. Second, Kirchberger et al. (2022)'s model does not fit perfectly. Thus, the need for a precise process model for digital twins is still valid. Similarly, the other objects in this category make use of organizational standardized process models that are aimed at other entities, such as the VDI 2206 (2021). This norm is targeting cyber-physical systems (cf. Graessler and Hentze 2020). Therefore, it comes very close to digital twins. In fact, it uses the V-Model for software implementation and, thus, is capable of guiding digital twin implementation. However, as time has already shown in other disciplines, e.g., simulation, organizational process models may exist (cf. VDI 3633 (2014)) but are accompanied by non-organizational frameworks whatsoever. For instance, Law (2019), Banks (1998), and many more provide further process models for simulation.

The next category is using machine learning algorithms as a process model. This category contains 1% of the objectives. Nevertheless, this category is interesting because machine learning algorithms are particularly suitable for modeling digital twins in real industrial systems due to their complexity (Wang et al. 2023). Wang et al. (2023) use the Sparse Identification of Nonlinear Dynamics Machine Learning Algorithm to model digital twins, which performs feature engineering by creating a library of model terms and then solving a sparse regression problem between the target outputs and the generated features.

Another category is workflow modeling. 1% of the objectives belong to the category of workflow modeling. A workflow model describes how organizational processes are structured to systematically achieve certain goals, such as the delivery of a product or service (Dumas 2009). Zhou and Liu (2022) use the artifact-centric workflow model ArtiFlow to represent the conceptual BP model of the software and use it after the description with XML for verification in the Stereoscopic Warehouse Digital Twin**.**

The last category is process mining, which accounts for 5% of the papers. Process mining is the process of gaining insight into business processes by extracting data from event logs, typically generated by systems such as enterprise resource planning, workflow management, or other process-supporting enterprise systems (van der Aalst 2011). Vitale et al. (2025) use process mining for the digital twin development of industrial cyber-physical systems.

5 DISCUSSION AND IMPLICATIONS FOR A BROADLY APPLICABLE PROCESS MODEL

The review so far has brought to light some very interesting aspects. The fact alone that exactly half of all the objects considered do not use a process model at all to implement a digital twin shows a major weakness in working with digital twins. Many projects set out to develop and introduce such a twin without a concrete concept behind it. This can be seen again and again in the analysis. In particular, the projects in which a twin is introduced without any process model indulge their own significance.

Basically, it can be said that a lack of a process model can lead to chaotic workflows. This lack of planning is often reflected in the fact that resources are needed on the spot and cannot be allocated proactively and efficiently. Suppose the process model is also understood as a checklist. In that case, a process model can help to identify missing elements and, at the same time, point out problems and errors during implementation at an earlier stage so that a much more expensive correction in later phases can be avoided. This is, of course, particularly the case if these process models have an accompanying evaluation in the early phases. The clear roles and responsibilities also simplify communication between the various stakeholders. Finally, a process model can also help to track the implementation process in retrospect and make it easier to understand, especially if a digital twin leaves the implementing company and is passed on with a product, allowing downstream stakeholders to understand the original implementation.

However, the trend towards greater use of process models should be emphasized. In a similar analysis from 2020, which focused on other aspects but also examined whether process models were used as a side objective, 59% of the objects considered were still underway without any process model or structured framework (van der Valk et al. 2020). In comparison, we found a structured procedure or a complete process model in every second project. The self-developed process models, which promise a well-structured procedure for the individual case, can undoubtedly be seen as an interim solution here. The fact that two-thirds of the objects do not apply a process model or just a self-developed one underlines the diversity of digital twins. They are applied in a variety of domains for multiple purposes; thus, the prioritization of individual aspects reflects itself in the process models. Nevertheless, even a very structured framework always allows for the adaptation of the process.

However, one-third of the objects also show the use of a standardized and regulated framework. This increases the various advantages of process modulation as mentioned above and, in particular, increases the comparability, reproducibility, and efficiency, whereby the susceptibility to errors and the correction effort are reduced. It is noticeable that no favorite process model has yet been prioritized and has been able to assert itself. This may be due to the fact that the topic of implementing digital twins is still relatively young, but also because the objects come from a wide variety of use cases with different framework conditions and correspondingly different catalogs of requirements for the digital twin. Mapping all these under a generic model is initially difficult if there is not already a model that can be regarded as the industry standard. This is also shown in Figure 4, where the domain dependency of the various identified procedures is shown in relation to the domains used.

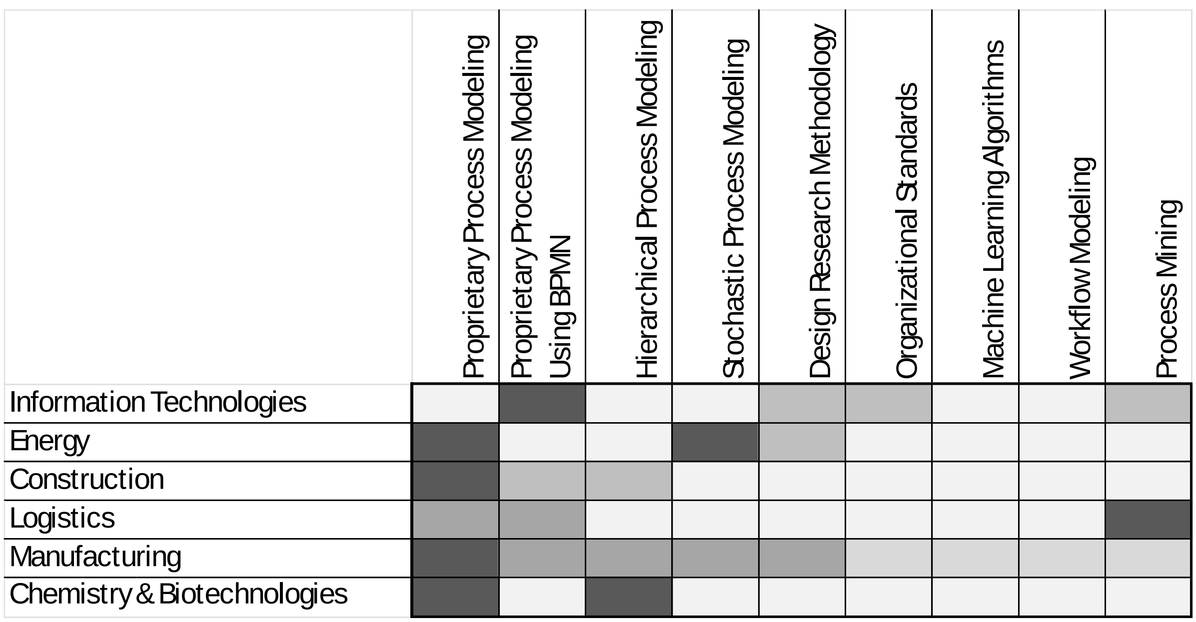

Figure 4: Domain dependency of the process models. Darker color indicates a higher share of hits.

In four of six domains, proprietary process modeling, i.e., the use of a process model as an in-house development, is the most common tool to be found. In two domains, the construction sector and manufacturing sector, it is even the only tool most frequently used. In the energy sector and in biotechnology and chemical technology, which also includes pharmacy, there is a second frontrunner with the stochastic process model (energy) and the hierarchical process model (biochemical technology).

In information technology, in-house developments are also frequently used but created with the help of BPMN. Finally, there is logistics, where the topic of process mining occurs particularly frequently. The distribution towards in-house developments (with BPMN) is hardly surprising. Since the majority of all objects use these two categories, it is also to be expected that they are domain-specific leaders.

However, it is also apparent that certain areas are particularly interesting for some domains. In information technology, these include design research methodology, and organizational standards. There are two reasons for this. On the one hand, the information sciences, on which information technologies are based, employ a great deal of the design science research approach, which designs artifacts. At the same time, this domain is very close to the engineering communities, which often follow standards and norms. For instance, it can be communication standards such as OPC UA or, in relation to a digital twin, ISO 23247. In addition, another aspect appears here within the domains. A variety of different process models are used. This is also quite common in the specific consideration of the number of objects, so different process models are used for partial aspects of a digital twin. For example, the simulation and the data flow follow two different process models, which must then be integrated with each other.

From the observations, a few implications were derived. An interesting aspect is the consideration of data management models that can help conceptualize different aspects of a digital twin, especially in data handling. Data products have existed for over 30 years, but can be interpreted as information products in a modern way and form an integral part of the digital twin. Following the definition of a data product, this is a managed artifact that is often data-based. Therefore, data management is essential for the services that a digital twin provides.

An example of such a framework is the Data Excellence Model by Legner et al. (2020), which describes various dimensions of business model generation, capabilities, and, above all, data management characteristics such as a data lifecycle or data architecture in terms of data excellence.

The evaluation shows the risks of not using a process model, such as inefficiencies, a lack of standardization, and missed potential commencement. In particular, the differences between manufacturing, for example, where many unstructured approaches are used, and logistics or the energy sector, where structured approaches are more common, show the disparity between the various use cases considered.

Strategic implications that can be derived from this are, on the one hand, the need for training. This can create a much better understanding of why process models should be used. In addition, acceptance of process models can be established as part of a data culture. There should be follow-up management for changes in the project, which can be better covered within the framework of process models.

The differences between the various domains, e.g., energy and logistics vs. manufacturing, also suggest that cross-industry knowledge transfer is necessary. Best practices from one sector can, thus, benefit the other. Obviously, projects that want to implement digital twins need technical support. This starts with the selection of suitable process models and associated software tools for implementation and includes guidance on the correct application of the same.

Ultimately, the use of process models can lead to excellence in processes and data management. This can create a better market position. Innovations can be better promoted. If the implementation itself runs more efficiently, more resources remain to try out and continue new approaches. As a consequence, a process model leads to a reduction in costs and risks that exist during implementation. It should be noted that a process model is structured in an interdisciplinary way to integrate the different views during implementation from the software side, from the process side, and from the business side. An efficient implementation process improves the work processes and boosts the satisfaction of the people involved. Nevertheless, standardization might also limit creativity and, thus, might harm dynamic developments. Furthermore, standards can bring costs, especially if they are too heavy for the purpose. Therefore, there is always a need for a balanced check whether the standardized process model fits the respective implementation process.

6 CONCLUSION

In this paper, we conducted a structured literature review and analysis in which we examined 38 papers about process models for digital twin implementations in detail. Following the vom Brocke et al. (2009) methodological approach, the structured literature reviews were conducted in five steps. The findings show that half of the papers do not apply a process model at all. Nevertheless, a positive trend towards applying process models is noticeable. Many objects also use self-made process models that provide structure for the implementation. Only one-third of the objects use standardized process models. The process models used also vary by domain. While proprietary models dominate manufacturing, stochastic models are more common in energy, process mining in logistics, and BPMN-driven approaches in information technologies.

Our work contributes to the scientific discourse on application-oriented research on digital twins. The review provides a comprehensive overview of the state of the art of process design for implementation processes. We could identify common approaches and, therefore, could empirically derive implications for a generic process model. Special features of domains and different approaches can be weighed against each other. Thus, researchers and practitioners alike can choose working approaches for their digital twin development. Furthermore, practice-oriented projects can build upon the implications and tailor one of the portrayed process models for piloting a digital twin for industrial use.

Our work is subject to certain limitations. An SLR always has the danger of becoming too subjective. Therefore, we paid particular attention to objectivity in every step. We reflected on any decisions and discussed the results with research experts for digital twins and process models. During the data acquisition, we aimed for high quality in the objects for analysis to further support the results. Yet, another team of researchers may come to other results as the data constantly evolves, and new insights might be published after this research is finished. A regular update on the literature work will enhance the quality for the future.

Additionally, our work reflects the state of the art in research. We seek to include empirical insights from industry and operational applications in further research. We also aim at a short-term development of standardized process models for multiple digital twin domains and use cases, before the empirical insights become obsolete. This standardized model will guide practitioners to an easier, faster, and more efficient implementation process of digital twins. Other aspects of further research are analyzing challenges within the implementation process and developing a business model for digital twin applications.

ACKNOWLEDGMENTS

This work was partially funded by the project "Digital Ecosystem for a Sustainable Circular Economy in the Automotive Industry" (DIONA). The project DIONA is funded by the German Federal Ministry of Education and Research.

REFERENCES

Banks, J. 1998. *Handbook of Simulation*. Hoboken: John Wiley & Sons, Inc.

Becker, J., M. Rosemann, and R. Schütte. 1997. "Business-to-Business-Process Integration: Functions and Methods". In *Proceedings of the 5th European Conference on Information Systems (ECIS' 97)*, June 19th-21st, Cork, UK.

Boschert, S. and R. Rosen. 2016. "Digital Twin - The Simulation Aspect". In *Mechatronic Futures*, edited by P. Hehenberger and D. Bradley, 59–74. Cham: Springer International Publishing.

Brassey, J., A. de Smet, D. Maor, S. Rabipour. 2024. *Developing a Resilient, Adaptable Workforce for an Uncertain Future*. Luxembourg: McKinsey Quarterly.

Canzoneri, M., A. de Luca, and J. Harttung. 2021. "Digital Twins: A General Overview of the Biopharma Industry". *Advances in Biochemical Engineering/Biotechnology* 177:167–184.

Compagnucci, I., F. Corradini, F. Fornari, and B. Re. 2024. "A Study on the Usage of the BPMN Notation for Designing Process Collaboration, Choreography, and Conversation Models". *Business & Information Systems Engineering* 66(1):43–66.

Cooper, R. G. 1983. "A Process Model for Industrial New Product Development". *IEEE Transactions on Engineering Management EM* 30(1):2–11.

Da Torres, I. S., M. Fantinato, G. M. Branco, and J. Gordijn. 2023. "Guidelines to Derive an E3 Value Business Model from a BPMN Process Model: An Experiment on Real-World Scenarios". *Software and Systems Modeling* 22(2):599–618.

Disselkamp, J.-P., R. Grothe, J. Lick, B. Schütte, S. Brüne, L. Schröder, and R. Dumitrescu. 2024. "Towards the Digital Factory Twin – Design Guide for Creating a 3D Factory Model", *In Proceedings of the Design Society*, May 20th-23rd, Dubrovnik, Croatia, 1979–1988.

Dumas, M. 2009. "Workflow Modeling". In *Encyclopedia of Database Systems*, edited by L. Liu, 3551–3557. New York: Springer.

Figl, K., A. Koschmider, and S. Kriglstein. 2013. "Visualising Process Model Hierarchies". In *Proceedings of the 21st European Conference on Information Systems (ECIS 2013)*, June 5th-8th, Utrecht, Netherlands.

Fortune. 2024. *Digital Twin Market*. Pune, India: Fortune Business Insights.

Ghasemi, A., S. Lazarova-Molnar, and C. Heavey. 2024. “Supply Chain Digital Twin Framework for Hybrid Manufacturing Strategy Selection: A Case Study from the Semiconductor Industry”. In *2024 Winter Simulation Conference (WSC)*, 2951–2962 https://doi.org/10.5555/3712729.3712974.

Göllner, D., S. Dzienus, R. Rasor, H. Anacker, and R. Dumitrescu. 2023. “Guidelines for Providing Digital Twins”. *Procedia CIRP* 120:1433–1438.

Graessler, I. and J. Hentze. 2020. “The new V-Model of VDI 2206 and its Validation”. *at - Automatisierungstechnik* 68(5):312–324.

Grieves, M. 2023. “Digital Twins: Past, Present, and Future”. In *The Digital Twin*, edited by N. Crespi, A. T. Drobot, and R. Minerva, 97–121. Cham: Springer International Publishing.

Grieves, M. 2014. *Digital Twin: Manufacturing Excellence Through Virtual Factory Replication*. Cocoa Beach: Michael W. Grieves LLC.

Heininger, R., T. E. Jost, and C. Stary. 2024. “Developing and Operating Digital Process Twins While Preserving Autonomy in CPS”, In *26th International Conference on Business Informatics (CBI)*, September 10th-13th, Vienna, Austria, 50–59.

Herberger, T. A. and J. J. Dötsch. 2021. *Digitalization, Digital Transformation and Sustainability in the Global Economy*. Cham: Springer International Publishing.

IDTA. 2023. Der Standard für den Digitalen Zwilling. https://industrialdigitaltwin.org/, accessed 11th April.

ISO 23247. 2021. *Automation Systems and Integration - Digital Twin Framework for Manufacturing - Part 1: Overview and General Principles*. Geneva: ISO.

Jones, D., C. Snider, A. Nassehi, J. Yon, and B. Hicks. 2020. “Characterising the Digital Twin: A Systematic Literature Review”. *CIRP Journal of Manufacturing Science and Technology* 29:36–52.

Kirchberger, M., M. Heeger, A. Altay, C. Liebrecht, L. Overbeck, M. Kandler, G. Lanza, C. Voigt, and J. Franke. 2022. "A Simulation-based Process Model for the Realization of a Matrix Manufacturing System Planning, Evaluation and Digital Twin in the Electronics Industry at Siemens AG Karlsruhe". *ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb* 117(4):224–228.

Kolditz, O., D. Jacques, F. Claret, J. Bertrand, S. V. Churakov, C. Debayle, D. Diaconu, K. Fuzik, D. Garcia, N. Graebling, B. Grambow, E. Holt, A. Idiart, P. Leira, V. Montoya, E. Niederleithinger, M. Olin, W. Pfingsten, N. I. Prasianakis, K. Rink, J. Samper, I. Szöke, R. Szöke, L. Theodon, and J. Wendling. 2023. “Digitalisation for Nuclear Waste Management: Predisposal and Disposal”. *Environmental Earth Sciences* 82(1):42.

Law, A. 2019. “How to Build Valid and Credible Simulation Models”. In *2019 Winter Simulation Conference (WSC)*, 1402–1414 https://doi.org/10.1109/WSC40007.2019.9004789.

Legner, C., T. Pentek, and B. Otto. 2020. “Accumulating Design Knowledge with Reference Models: Insights from 12 Years’ Research into Data Management”. *Journal of the Association for Information Systems* 21(3):735–770.

Li, Q., and F. Hu. 2024. “Digital Twin-Enabled Channel Access Control in Industrial Internet of Things”, In *2024 IEEE/CIC International Conference on Communications in China (ICCC)*, August 7th-9th, Hangzhou, China, 2149-2154.

Lüder, A., A.-K. Behnert, F. Rinker, and S. Biffl. 2020. “Generating Industry 4.0 Asset Administration Shells with Data from Engineering Data Logistics”. In *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*, September 8th-11th, Vienna, Austria, 867–874.

Mallek-Daclin, S., N. Daclin, S. Rabah, and G. Zacharewicz. 2023. “Product Development Plan Monitoring: Towards a Business Process Digital Twin”. *IFAC-Papers Online* 56(2):11894–11899.

Mohammadi, N., and J. E. Taylor. 2018. “Smart City Digital Twins”. In *2017 Symposium Series on Computational Intelligence Proceedings*, November 27th – December 1st, Honolulu, HI, USA, 1–5.

Peffers, K., T. Tuunanen, M. A. Rothenberger, and S. Chatterjee. 2007. “A Design Science Research Methodology for Information Systems Research”. *Journal of Management Information Systems* 24(3):45–77.

Recker, J., H. A. Reijers, and S. G. van de Wouw. 2014. “Process Model Comprehension: The Effects of Cognitive Abilities, Learning Style, and Strategy”. *Communications of the Association for Information Systems* 34:199–222.

Ritter, L. and K. Sobania. 2024. *Digitalisierung weiter eher Werkzeug als Innovationsmotor*, Berlin: DIHK.

Ryu, S., J. Jung, B. Song, and J. Shin. 2024. "Development of Robot Applications Utilizing Asset Administration Shell for Integrated Robotics Processes". In *2024 IEEE 29th International Conference on Emerging Technologies and Factory Automation (ETFA)*, September 10th-13th, Padova, Italy, 1–4.

Salinas Segura, A., M. Angos Mediavilla, L. Braun, M. Freund, C. Kosel, and M. Rodriguez. 2024. “A Process Model for Deriving Asset Administration Shells for Inter-company Collaboration – A Practical Approach”. In *Systems, Software and Services Process Improvement. EuroSPI 2024. Communications in Computer and Information Science, vol 2180*, edited by M. Yilmaz, P. Clarke, A. Riel, R. Messnarz, C. Greiner, and T. Peisl, 217–229. Munich: Springer.

Salvi, A., P. Spagnoletti, and N. S. Noori. 2022. “Cyber-Resilience of Critical Cyber Infrastructures: Integrating Digital Twins in the Electric Power Ecosystem”. *Computers and Security* 112:102507.

Sarantinoudis, N., G. Tsinarakis, and P. Dedousis. 2023. “Model-Based Simulation Framework for Digital Twins in the Process Industry”. *IEEE Access* 11:111701–111714.

Schmidt, A., H. Helgers, L. J. Lohmann, F. Vetter, A. Juckers, M. Mouellef, S. Zobel-Roos, and J. Strube. 2022. “Process Analytical Technology as Key-Enabler for Digital Twins in Continuous Biomanufacturing”. *Journal of Chemical Technology and Biotechnology* 97(9):2336–2346.

Schwede, C. and D. Fischer. 2024. "Learning Simulation-Based Digital Twins for Discrete Material Flow Systems: A Review". In *2024 Winter Simulation Conference (WSC),* 3070–3081 https://doi.org/10.1109/WSC63780.2024.10838729.

Sein, M. K., O. Henfridsson, S. Purao, M. Rossi, and R. Lindgren. 2011. "Action Design Research". *MIS Quarterly* 35(1):37–56.

Shafto, M., M. Conroy, R. Doyle, E. Glaessgen, C. Kemp, J. LeMoigne, and L. Wang. 2010. *DRAFT Modeling, Simulation, Information, Technology & Processing Roadmap: Technology Area 11*. Houston: NASA.

Sodachi, M., A. Pirayesh, and O. F. Valilai. 2024. "Using Markov Decision Process Model for Sustainability Assessment in Industry 4.0". *IEEE Access* 12:189417–189438.

Strobel, G., F. Möller, and H. van der Valk. 2022. "Healthcare in the Era of Digital Twins: Towards a Domain-Specific Taxonomy". In *Proceedings of the 30th European Conference on Information Systems,* June 16th-18th, Timisoara, Romania.

Tao, F., F. Sui, A. Liu, Q. Qi, M. Zhang, B. Song, Z. Guo, S. C.-Y. Lu, and A. Y. C. Nee. 2019. "Digital Twin-Driven Product Design Framework". *International Journal of Production Research* 57(12):3935–3953.

Tomczyk, M., and H. van der Valk. 2022. "Digital Twin Paradigm Shift: The Journey of the Digital Twin Definition". In *Proceedings of the 24th International Conference on Enterprise Information Systems*, edited by J. Filipe, M. Smialek, A. Brodsky, and S. Hammoudi, 90–97. Cham: Springer.

Tuegel, E. 2012. "The Airframe Digital Twin: Some Challenges to Realization". In *Structures, Structural Dynamics, and Materials and Co-located Conferences: 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April 23rd-26th, Honolulu, HI, USA, 1812.

van der Aalst, W. 2011. *Process Mining: Discovery, Conformance and Enhancement of Business Processes*. Berlin, Heidelberg: Springer.

van der Valk, H., R. Schmelzer, D. Rose, and B. Dinter. 2024. "Towards a Process Model for Digital Twin Implementation: The Implementation Canvas". *Procedia CIRP* (122):903–908.

van der Valk, H., H. Haße, F. Möller, and B. Otto. 2022. "Archetypes of Digital Twins". *Business & Information Systems Engineering* 64(3):375–391.

van der Valk, H., J.-L. Henning, S. Winkelmann, and H. Haße. 2022. "Practical Requirements for Digital Twins in Production and Logistics". In *Proceedings of the Conference on Production Systems and Logistics*, edited by D. Herberger and M. Hübner, 32–41. Hannover: publish-Ing.

van der Valk, H., J. Hunker, M. Rabe, and B. Otto. 2020. "Digital Twins in Simulative Applications: A Taxonomy". In 2020 Winter Simulation Conference (WSC), 2695–2706 https://doi.org/10.1109/WSC48552.2020.9384051.

VDI. 2021. *VDI 2206 Development of Mechatronic and Cyber-Physical-Systems*. Düsseldorf: Beuth.

VDI. 2014. *Simulation of Systems in Materials Handling, Logistics, and Production: Part 1 - Fundamentals*. Berlin: Beuth.

Vitale, F., S. Guarino, F. Flammini, L. Faramondi, N. Mazzocca, and R. Setola. 2025. "Process Mining for Digital Twin Development of Industrial Cyber-Physical Systems". *IEEE Transactions on Industrial Informatics* 21(1):866–875.

vom Brocke, J., A. Simons, B. Niehaves, K. Reimer, R. Plattfaut, and A. Cleven. 2009. "Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process". In *Proceedings of the 17th European Conference on Information Systems,* June 8th-10th, Verona, Italy.

Wang, J., J. Moreira, Y. Cao, and R. B. Gopaluni. 2023. "Neural Network and Sparse Identification of Nonlinear Dynamics Integrated Algorithm for Digital Twin Identification". *IFAC-Papers Online* 56(2):6921–6926.

AUTHOR BIOGRAPHIES

ANNIKA HESSE is a researcher in the Chair of Industrial Information Management at TU Dortmund University. She holds a Master of Science in Industrial Engineering with a focus on Industrial Management from TU Dortmund University. Her research focus are data management tools and data products in industrial contexts. She examines reference models for data management. Additionally, she leads the chair's efforts in implementing design thinking as engineering processes in information science. She conducts her research as a member of the DIONA project on circular economy. Her e-mail address is annika.hesse@tu-dortmund.de, and her website is https://iim.mb.tu-dortmund.de/team/annika-hesse/.

HENDRIK VAN DER VALK is the chief engineer at the Chair for Industrial Information Management at TU Dortmund University, supervising the departments of Data-Driven Value Chains and Data Ecosystems, and is scientific coordinator at the Fraunhofer Institute for Software and Systems Engineering. His research focuses on the data-driven circular economy, digital twins, and data ecosystems. Also, his research interests lie in the field of reference architectures and procedure models. He holds a PhD in Mechanical Engineering from TU Dortmund University. He is currently a member of the Digital Twin Hub, the Institute for Operations Research and the Management Sciences INFORMS, the German Chapter of the Association for Information Systems, the German Association of Information Systems, and the Circular Economy Digital Hub Initiative. His email address is hendrik.van-der-valk@tu-dortmund.de, and his website is https://iim.mb.tu-dortmund.de/team/hendrik-van-der-valk/.