Digital Twins for Machine Tools: A Systematic Mapping Study

Shengjian Chen[1], Carsten Ellwein[1], Lars Klingel[1], Rebekka Neumann[1], Jingxi Zhang[1], Oliver Riedel[1], Alexander Verl[1], Andreas Wortmann[1]

[1]Institute for Control Engineering of Machine Tools and Manufacturing Unit (ISW), University of Stuttgart, Seidenstr. 36, Stuttgart, 70174, BW, Germany.

Contributing authors: shengjian-patrick.chen@isw.uni-stuttgart.de; carsten.ellwein@isw.uni-stuttgart.de; lars.klingel@isw.uni-stuttgart.de; rebekka.neumann@isw.uni-stuttgart.de; jingxi.zhang@isw.uni-stuttgart.de; oliver.riedel@isw.uni-stuttgart.de; alexander.verl@isw.uni-stuttgart.de; andreas.wortmann@isw.uni-stuttgart.de;

Abstract

Machine tools are essential for modern manufacturing and drive the production of precise and high-quality components across various industries. For smart manufacturing, DTs–virtual representations of cyber-physical entities–have emerged to enhance machine tools with intelligent capabilities, such as real-time monitoring, predictive maintenance, or performance optimization. Despite their potential, the availability and application of Digital Twins in machine tools remain largely unexplored. This first systematic mapping study specifically on Digital Twins for machine tools investigates the purpose for their deployment to machine tools, the development methods to create such Digital Twins, and support for their connectivity to the machine tool and to other related systems. Our findings highlight the critical role of DTs in improving the efficiency and reliability of machine tools.

Keywords: Smart Manufacturing, Digital Twin, Machine Tool, Systematic Mapping Study

1 Introduction

Machine tools play a pivotal role in modern manufacturing. They enable the production of precise and high-quality components across various industries. As industry moves towards smart manufacturing paradigms that use digital technologies and networking [87, 93, 128, 138] to react to changing requirements within a system in real time [112], the concept of digital twins (DTs) [98, 117, 141] has emerged as a critical technological backbone.

A DT is a virtual representation of a (cyber-) physical asset that uses data, models, and services to improve understanding [123] and operation [92] of the asset. For machine tools, DTs can be used to provide real-time insights and optimize performance. Despite the growing interest in DT technology, a comprehensive evaluation of its availability and applicability specifically for machine tools has not been thoroughly evaluated. The lack of dedicated studies on this topic highlights the urgent need for focused research to address existing limitations and promote the integration of DT technology in the manufacturing industry. This study contributes to the field by offering a detailed overview of use and development of DTs for machine tools and identifying key areas for future research and development.

Our investigation of the current landscape of DT solutions for machine tools over the past five years aims to address this gap. Through a systematic mapping study (SMS) [129], we assess the extent to which DT solutions are available. Our findings reveal significant disparities in the maturity and accessibility of DT solutions across different machine tool applications.

In the remainder, Section 2 outlines the method of systematic mapping studies and distinguishes it from the method of systematic literature reviews. Then, Section 3 discusses how our survey differs from related studies, before Section 4 details our research method, questions, queries, and data collection. Afterward, Section 5 provides answers to our research questions. Then, Section 6 summarizes our findings, based on which Section 7 outlines the steps of a research roadmap for the deployment of DTs for machine tools. Section 8 discusses threats to validity and Section 9 concludes the paper. The data for replication are available online[1].

2 Methodical Background

A SMS is a well-established method of literature analysis [129, 130] that has been applied to a variety of domains, including automotive [106], computer science [78], manufacturing [142], robotics [91], healthcare [136], and more [143] to better understand their particular landscape of (research) literature. The primary objective of a systematic mapping study is to identify the necessity for subsequent research. Thus, an SMS aims to identify and categorize publications within a specific research field based on predefined, structured criteria [129], without the requirement of evaluating the contribution to the field. This method provides a comprehensive overview of topics and types of contributions in a given field, facilitating the analysis of the current state, challenges, and overall progress. Thus, a SMS identifies research areas not covered by the literature for a comprehensive overview of contributions in a given field. To ensure replicability, a SMS adheres to well-documented and widely accepted process guidelines [114, 129] as outlined in Section 4. In contrast, a systematic literature review (SLR) seeks to identify conceptual contributions to existing or derived theories [104], where the analysis may be chronological, conceptual, or thematic. Therefore, SLRs identify the most significant items in a given field and investigate their contributions in detail w.r.t. to the research questions of the SLR. Thus, a SLR also includes a quality assessment, whose evaluation depends on its contribution to the field. Consequently, quality assessment can determine the inclusion or exclusion of a particular literature–something a SMS usually does not foresee for prevent restricting the view on the field of investigation [130].

3 Related Studies

Various studies have already been conducted to investigate the various characterizations of DTs and their practical applications. This includes a comprehensive overview of 19 distinct DT characteristics, which encompass a range of factors including environment and connectivity factors, as well as the fidelity of the physical and virtual counterparts within a DT system [111]. In a cross-domain SMS, the authors investigated the usage of DTs in various domains. They examined the twinning targets, system lifecycle phases, and twin lifecycle phases in more than 350 publications on DT applications. However, the study did not address issues specific to machine tools, such as the process or the real-time capability of the DT. Several other reviews have focused on specific concepts related to the broader application of DTs in manufacturing and its processes, such as Industry 4.0 [96], digital factories [125], cyber-physical production systems [126], zero-defect manufacturing [133], and manufacturing process modeling [120]. These reviews also did not consider DTs of machine tools.

Another comprehensive overview focuses on state-of-the-art DT technology and its application in various stages of the machine tool lifecycle and process design [80]. The authors highlight the current application areas and technologies for DTs in the context of machine tools, which they term "virtual machine tools". The authors concentrate on unidirectional information flow from physically heterogeneous machines to a network for analytics and front-end processing. Benefits outlined

[1]Replication package: https://doi.org/10.18419/darus-4542

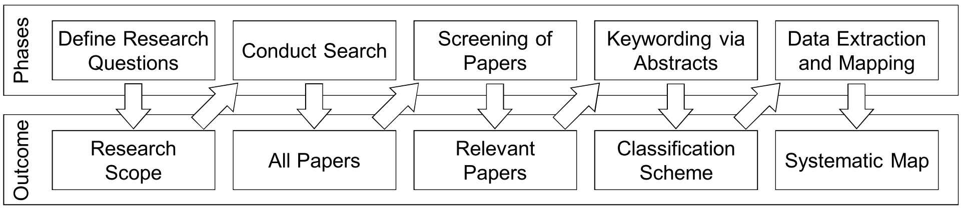

Figure 1: Phases and outcomes of an SMS [129]

include leveraging models to enhance performance based on real-time data from monitored inputs using simulation models for virtual commissioning. Furthermore, they employed simulation models for health monitoring through anomaly detection. The study also addressed the issue of machine component failure at the end of the machine tool lifecycle, emphasizing energy consumption as a critical feature. Examples of network interfaces include the Open Platform Communications Unified Architecture (OPC UA) [119, 127], cloud infrastructure, and existing cyber-physical systems. That review notably lacks a systematic overview, replicability, and direct discussion of technology readiness levels. Additionally, it does not explicitly include real-time communications.

Another literature review of DT modeling for machine tools is limited to a single database of articles and found a total of 82 papers [149]. This study focuses on identifying enabling technologies for machine tool intelligence based on, as the authors describe it, "digital twin technology". The paper then discusses the state of the art in DT modeling, focusing on examining it from the aspects of data-based modeling and mechanism data. Additionally, it highlights three bottlenecks in this field. Considering these issues, the paper proposes an architecture for a DT for machine tools and explains three key technologies: data perception and fusion technology, mechanism-data-knowledge hybrid-driven DT modeling, and virtual-real synchronization technology, as well as dynamic optimization and collaborative control technology for multi-level parameters.

Although these existing studies provide an overview of the possible DT applications in manufacturing, extensive studies on DTs and their applications on machine tools are lacking. Thus, our goal is to address this gap by researching the use of DTs for machine tools in manufacturing.

4 Research Method

We conducted an SMS to examine analyze the DT research landscape for machine tools. To this effect, we applied established guidelines and drew on methodologies from other systematic mapping studies [89, 95, 116, 148]. Consequently, we implemented the standard five-phase process of systematic mapping studies [129] as outlined in Figure 1: (1) Define research questions; (2) Search for publications; (3) Establish inclusion and exclusion criteria and filter the publications accordingly; (4) Classify the publications using keywording; and (5) Extract and aggregate the relevant data. In our study, we implemented these five phases as described in the following:

1. Define Research Questions: In the first phase, we established the scope of the SMS, which encompassed the research questions and primary topics of interest for the publications under consideration. Specifically, we are interested in the purpose of the DT for machine tools. This includes investigating the life cycle of the reference Architectural Model Industry 4.0 (RAMI 4.0) [107] model and, in particular, whether DTs are used to mitigate the gap between the design and runtime of a system through virtual commissioning. The research questions are detailed in Section 4.1.

2. Conduct Search: In the second phase, we collected a set of potentially relevant publications. To this end, we decided to compile as many related publications as possible by using the following broad query in large and reliable[2] literature databases:

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"digital twin" AND "machine tool"
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[2]See discussion on issues with Google Scholar in Section 8.

This process is explained in detail in Section 4.2.

3. Screening of Papers: Prior to screening the papers, we defined inclusion and exclusion criteria to ensure that relevant papers were not accidentally removed from the corpus. Each author screened the first 60 papers individually. Then, we had a joint discussion to prevent misunderstandings regarding the inclusion and exclusion criteria detailed in Section 4.3. Then, the remaining papers were divided among the authors, who screened them individually. In case of uncertainty, the papers were discussed in the group and screened again by at least one other author.

4. Keywording via Abstracts: In this phase, we reviewed the abstracts of the remaining papers and identified the keywords relevant to the research questions. These were documented in our search protocol, which ultimately resulted in the classification schema presented in Section 4.4.

5. Data Extraction and Mapping: In the final phase, we reviewed each paper comprehensively by completely reading it and using the search protocol to complete the classification schema for each paper. The results of this are presented in Section 5.

4.1 Research Questions

The purpose of this SMS is to identify and review publications on DTs for machine tools to better understand how they are used, developed, evaluated in the context of machine tools. Therefore, our investigation focuses on several key aspects, including how DTs are defined in the context of machine tools, the development processes and engineering methods used for DTs, and the communication mechanisms used for integration and operation. By mapping these elements, we aim[3] to document the current state-of-the-art DT technology for machine tools. The following three main research questions the their sub-questions encapsulate our research interest:

[3] Not every publication will address (all of) these questions, hence, there may be questions that cannot be answered by a SMS.

RQ-1. What does the digital twin describe and when is it used?

The following research questions aim to identify what exactly is twinned in the context of machine tools and why:

RQ-1.1 What does the DT describe? A machine does not have to be entirely represented by the DT. Individual components, such as the machine control system or spindle motor controls, can also be twinned. Conversely, machine combinations can also be represented. This question aims to clarify which cyber-physical counterparts are described by the DT.

RQ-1.2 What is the purpose of the DT? This question aims to understand why DTs for machine tools are being developed and used.

RQ-1.3 How is the DT classified in the Product-Process-Resource (PPR) model? In the industrial manufacturing domain, three key aspects exist: products, processes and resources. Products are realized by processes carried out by resources. This question aims to identify the placement of the DT within the PPR model.

RQ-1.4 Which production process is being twinned? Machine tools have been used to perform various manufacturing processes. These processes are specified according to the third level of DIN 8580 [94], which is defined by the German Institute for Standardization. This question aims to identify the manufacturing processes for which DTs are used.

RQ-1.5 In which life cycle phase of the RAMI 4.0 model is the system represented by the DT? DTs can be used in several phases of the RAMI-4.0 [107] physical asset lifecycle. This question aims to identify the lifecycle phases in which DTs are used.

RQ-1.6 If virtual commissioning is used, how is the DT of the machine tool realized? According to the Association of German Engineers (VDI) defined in VDI 3693 [109], three configurations of virtual commissioning exist: Model-in-the-Loop (MiL), Software-in-the-Loop (SiL), and Hardware-in-the-Loop (HiL) which differ in level of detail and realism.

RQ-2. How are digital twins developed?

This question aims to examine the comprehensive DT development process. Our goal is to provide a clear picture of the methodologies and tools used. The corresponding related research questions are as follows:

RQ-2.1 What are the components of the DT? Similar to real physical machine tools, DTs can be composed of various components, each of which serves a specific function within the overall system. This question seeks to identify and describe the various entities that comprise a DT.

RQ-2.2 Which models are used in the development process and what is their purpose? This research question aims to identify the types of models used during the development of DTs for machine tools. Examining the use of different models, such as kinematic, physics-based, or data-driven models, aims is to gain an understanding of the modeling techniques [**?**] and paradigms [79] that underpin the development of DTs.

RQ-2.3 Which software is used for developing DTs? In addition to the components and models used in and for DTs, we are interested in the tools used during development. This question aims to investigate Whether there are trends in the tools used for the DT implementation.

RQ-2.4 How is the DT visualized? Visualization techniques can be applied to DTs to better understand the behavior of the cyber-physical system. This question aims to determine whether DTs are visualized and to examine the tools and technologies used.

RQ-2.5 How are DTs composed? Reusability is key to efficient software engineering. For DTs, this could mean that DTs with complex systems are built up from less complex subsystem DTs.

RQ-2.6 What is the technical readiness level of the DT? This question aims to assess the maturity of the DTs for machine tools. Investigating the technical readiness level (TRL), helps us determine how close the DT is to being fully operational and integrated into practical applications.

RQ-3. How are digital twins connected and how do they communicate?

This question explores the mechanisms and technologies through which DTs are connected and communicate. DTs can communicate with each other, or with other systems and software. This research question is subdivided into the following questions:

RQ-3.1 Is the DT capable of actively communicating with the original, and if so, how? This question examines whether the DT can actively receive data from and send data to its PT.

RQ-3.2 Does the DT communicate with other systems? This question examines whether the DT is capable of communicating horizontally with other systems. With this question, we aim to understand the interoperability of a DT with its environment, including other DTs [121].

RQ-3.3 Is the DT capable of real-time communication and computation? This question investigates whether the DT can send or receive data in real-time, whether it can compute the data in real time, as well as which technologies are used for real-time communication and computation.

4.2 Search Queries and Data Sources

A well-designed search strategy is essential for identifying relevant publications that can answer the research questions. Formulating an appropriate search query and selecting the relevant libraries are essential steps in this process. Since our objective is to explore the application of DTs for machine tools in different domains and contexts, we did not further restrict our search terms. Consequently, we searched the selected databases using the terms `"digital twin" AND "machine tool"`. The databases chosen for this SMS are the ACM Digital Library, IEEE Xplore, Scopus, SpringerLink, and Web of Science (WoS). We omitted Google Scholar owing to its issues with structured literature retrieval [83] to ensure the quality of the included sources.

4.3 Screening Publications

In the classification phase of a SMS, a study's inclusion is generally determined by various factors, such as its accessibility, title, abstract, and keywords [129]. To ensure the study's replicability, we applied specific inclusion and exclusion criteria as follows:

Inclusion criteria

1. Studies published in peer-reviewed sources, such as journals, conferences, and workshops, within the last five years.
2. Studies are accessible electronically.
3. Studies are available in English.
4. Studies where we could deduce from the title, abstract, or keywords that their main topic is the conception or application of DTs for machine tools.
5. Studies published in 2018 or later (as the term DT gained popularity across various domains after 2018).

Exclusion criteria

1. Studies from sources without systematic peer review processes, such as books, magazines, and websites.
2. Short papers of less than five pages excluding references, such as editorials and reviews.
3. Studies where DTs are related work, additional applications, or a broader context.
4. Studies presenting literature reviews on DTs (discussed as related work).
5. Studies not featuring the terms "digital twin" and "machine tool" appeared in abstract, title, or keywords (which rules out publications using any of these terms, e.g., in the bibliography only).

We included a publication into our corpus if it matched *all* the inclusion criteria and *none* of the exclusion criteria. In case of doubt regarding exclusion, we decided to include the publication in the corpus for full-text reviewing, and potential exclusion based on that, in the next phase.

Then, each author analyzed and classified the first ten (about five percent) publications of the 187 potentially relevant publications of the corpus to build a shared understanding of DTs, the research questions, and the classification schema. Afterward, we discussed the results of our analysis to align our understanding of the publications, our analyses, and the research methodology. To classify the remaining 187 publications based on our exclusion criteria, we distributed these among the authors. Then, each author reviewed each full paper assigned and either excluded it or extracted the data according to our classification schema (cf. Section 4.4). This resulted in 76 papers left for analysis in this study.

We conducted extensive weekly discussions about the classification, exclusion, and inclusion of publications to improve our collective understanding of the topic. These discussions led to the exclusion of additional publications and improved our consensus regarding the classification schema. During the review process, we excluded further unrelated publications. Importantly, exclusions were not based solely on the venue of publication or comprehensibility of the content. No additional quality evaluation was performed during the process.

4.4 Classification Schema

To investigate the DTs appropriately, we developed a corresponding classification schema. Inspired by [129], we adapted the schema for the DT landscape for machine tool research.

Contribution Type Facet: Distinct papers may encompass different elements of a given research contribution. In line with the classification set forth in [129], we categorized the aforementioned publications according to the type of contribution they provided most strongly. To determine the overall benefit provided by the contributions described in the analyzed papers, we employed five contribution types, outlined in [129]:

- *Analyses* - Papers that present investigations without offering constructive contributions.
- *Concepts* - Papers presenting new methodologies for reasoning about things, such as new meta-models or taxonomies.
- *Methods* - Papers proposing methods of doing things.
- *Metrics* - Papers presenting methodologies for measuring things.
- *Tools* - Papers describing novel software tools related to the implementation of DTs.

Each publication was classified by a single contribution type.

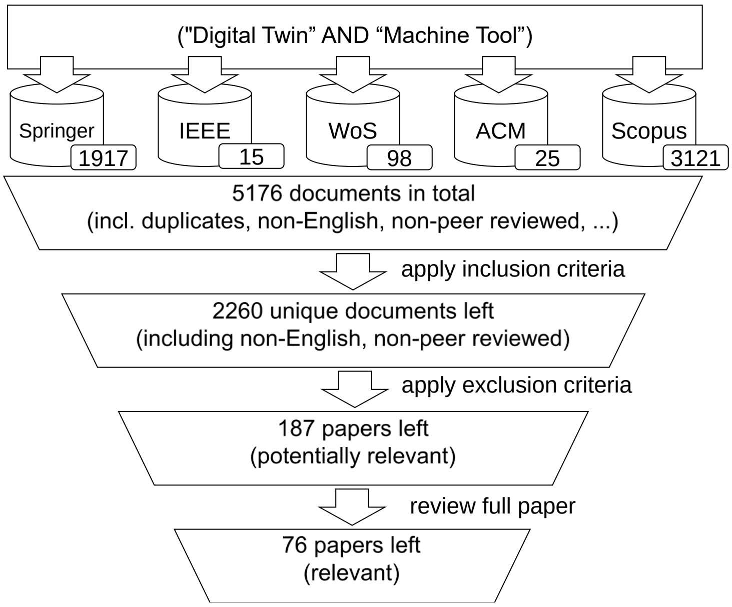

Figure 2: Data collection initially produced 2260 unique documents, out of which 76 papers were identified as relevant for our study.

Research Type Facet: Another important question relates to the type of research elaboration. It describes how the findings are conducted and presented. Inspired by [129], we classified publications by their research type. We adjusted the originating classes to better align with the corpus by excluding philosophical facets, as these did not fall within the scope of the study. The five research types are as follows:

1. *Evaluation* - Papers evaluating existing techniques.
2. *Experience* - Papers reporting personal experiences.
3. *Solution* - A novel solution is presented and argued for with case studies.
4. *Validation* - Papers presenting novel techniques and experimenting with them.
5. *Vision* - Research agendas, e.g., a vision of Artificial Intelligence (AI)-based DT engineering.

These five facets provide an overview of the research focus of the analyzed papers.

RQ-1. What does the digital twin describe and when is it used?

RQ-1.1 - DT Counterpart: When considering DTs for machine tools, manufacturing machines are often the first subject that comes to mind for twinning. To better understand what may be described by the DT in the context of this study, we investigate **RQ-1.1**. The DT is classified within the de facto standard framework of the hierarchical axis of RAMI 4.0 [107], inspired by the International Electrotechnical Commission (IEC) in IEC 62264 [101], namely the classes specified below:

- *Product* - i.e., a workpiece being manufactured
- *Field Level Device* - i.e., sensors and actuators
- *Control Unit* - i.e., Programmable Logic Controller (PLC) and Computerized Numerical Control (CNC)
- *Station* - i.e., a specific machine
- *Technical System* - i.e., the interlinking of machines, such as production lines
- *Enterprise* - i.e., a complete company
- *Connected World* - i.e., supply chains

We applied a single type of twin to each publication by leveraging this classification scheme.

RQ-1.2 - DT Purpose: Using DTs should yield benefits, such as behavior prediction [118] or advanced analysis [139]. Three main dimensions of the benefits of using technical systems have ultimately been identified: cost, time, and quality [81]. Consequently, we apply these three fundamental dimensions to our analysis.

- *Reduce Cost* - The costs during creation or operation can be reduced.
- *Improve Quality* - The quality of the machine tool itself and the products it produces can be improved.
- *Save Time* - The time required to provide or perform a specific processing step can be reduced.

These facets should be used to classify this question and determine whether the described improvement with the DT focuses on costs, time, quality, or a combination of these factors.

RQ-1.3 - Product-Process-Resource Categorization: There are three key aspects in production: products, processes, and resources [97]. Products are produced by processes which are carried out by resources. This relationship is depicted in the Product-Process-Resource (PPR) model [137]. To answer the question of what the DT is representing, we investigated where the considered DT is prescribed in the PPR Model. Our classification is based on which aspects are represented using the DT. This results in the following categories:

- *Product* - Products are manufactured with processes.
- *Process* - Processes are carried out by resources.
- *Resource* - Resources must be suitable for manufacturing the desired products.

A DT can represent one, several, or all of these aspects.

RQ-1.4 - Production Process: Manufacturing processes are characterized using DIN 8580 [94]. At the first level, processes are differentiated according to their main group (e.g., joining, forming, or separating). The second level distinguishes processes based on their properties, such as cutting with a geometrically defined or undefined cutting edge. The third level further divides these into subgroups, which we use to categorize executed and twinned processes of machine tools. The six categories identified in the relevant papers are listed below:

- *Drilling* - Drilling is a production process that involves creating holes in a material using a rotating cutting tool.
- *Grinding* - Grinding is a production process that uses an abrasive geometrically undefined cutting edge to remove material from a workpiece, achieving a high surface finish and precise dimensions. It is a subtractive process used for finishing operations.
- *Milling* - Milling is a production process that uses a rotating tool with geometrically defined cutting edges to remove material from a workpiece. It is a subtractive process used to shape, contour, and create precise features on a material.
- *Knife Cutting* - Knife cutting is a production process that uses a sharp blade to cut materials into the desired shapes and sizes. It is a subtractive process commonly used in industries such as textiles, packaging, and food processing.
- *Pressure Die Casting* - Pressure die casting is a production process in which molten metal is injected into a mold cavity under high pressure. This production process is used to produce complex shapes with high precision.
- *Punching* - Punching is a subtractive process that efficiently removes material in predetermined shapes.

If production processes were described in the works, they were categorized according to processes in the third level of DIN 8580. Multiple processes could be selected.

RQ-1.5 - DT Life Cycle Phase: DTs can be used in different phases of the life cycle. During the development phase, it can be used to plan the physical counterpart. During the operational phase, it can be used for monitoring and optimization. For this research question, we characterize the DTs described in the current academic publications, consistent with **RQ-1.1**, according to the RAMI 4.0 life cycle phases [107], inspired by IEC 62890 [102], i.e., development and operation.

In the RAMI 4.0 model, entities are classified as types or instances. Types refer to product families or products without serial numbers, while instances have serial numbers. This results in the following categories:

- *Development Phase, Type* - In the development phase for types, DTs are used, e.g., to design, simulate, and optimize the specifications before any physical instance is created.
- *Development Phase, Instance* - In the development phase for instances, DTs are used to prototype and test specific, individual products, processes, or systems, to ensure they meet the designed specifications and performance criteria.
- *Operational Phase, Type* - In the operational phase for types, DTs monitor and analyze aggregated data from multiple instances to improve the overall design, identify common issues, and enhance future iterations.
- *Operational Phase, Instance* - In the development phase for instances, DTs provide monitoring, diagnostics, and predictive maintenance for individual products or systems to ensure optimal performance and reduce downtime.

The DT of each relevant work is characterized accordingly. It is possible to apply a single DT in multiple phases.

RQ-1.6 - Virtual Commissioning Configuration Type: Production resources can be realized using different virtual commissioning configurations based on VDI 3693 [?], which differ in terms of realism and realization effort. This results in the following categories:

- *Model-in-the-Loop* - MiL involves testing control sequences in an early stage of the engineering phase using a model of the control behavior, allowing for the early detection of design issues before hardware implementation.
- *Software-in-the-Loop* - SiL involves testing the control programs that will later run on the real system, within an emulated controller. This ensures that the software's functionality and performance are accurate and reliable before deployment on actual hardware.
- *Hardware-in-the-Loop* - HiL integrates real hardware components (e.g., controllers) with a simulated environment (e.g., machine), enabling realistic testing and validation of the system under real-time conditions.

The DT described in each relevant work is characterized accordingly. The rarity of mixing several configurations was not considered, and multiple answers were excluded.

RQ-2. How are digital twins developed?

RQ-2.1 - DT Constituents: DTs seem to be many different concepts for different stakeholders[4]. Consequently, DTs are constructed differently and in various parts. This research question investigates the components of these models, i.e., the different types of DTs. We employ the 5D model of DTs [141] (cf. Figure 3) as the classification framework of choice. Accordingly, a DT consists of the following five dimensions:

- *Data* - Obtained from or about the actual system;
- *Models* - Such as kinematics or CAM models;
- *Physical Entity* - Interfaces to sensors or actuators that are vital for observing or manipulating the actual system;
- *Services* - Added-value functions using models and data of the DT; and
- *Connections* - Integration between all dimensions.

Due to the diversity of the field, each reported DT may use constituents from multiple or all of these dimensions.

RQ-2.2 - DT Models: Models are essential for engineering production systems [148]. Such models are used for various purposes and follow different paradigms [79]. Hence, models of the actual system (e.g., CAD, CAM models [144] or function block models [146]) can be used in DTs to make use of data from and about the actual system, e.g., OPC UA information models [77] and data models [131]. Thus, we examine the purpose of models in the context of our study. It is possible that a single paper uses multiple model

[4] List of 112 definitions of "digital twin": www.wortmann.ac/digital-twin-definitions.

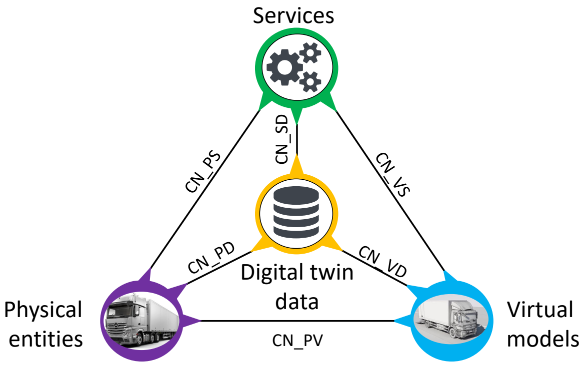

Figure 3: The 5 dimensions of DTs [141]

types, particularly given their different purposes. Based on the findings of a general mapping study on the engineering of DTs [92], we classify the models as follows:

- *Behavior Models* - Describe the functionality of a machine tool in its digital counterpart.
- *Structure Models* - Describe the structural composition of a machine tool.
- *Machine Learning Models* - Are trained models of processes, i.e., models used for optimization or anomaly detection.
- *Simulation Models* - Commonly used in the field of virtual commissioning.
- *Ontologies* - Represent relationships between a set of concepts within a domain.

The related purposes of the DT model as identified in the literature [98] are depicted in Figure 4:

- *Descriptive* - Models that reflect the system's environment in a descriptive manner. These models represent the current and past aspects of the system to improve understanding and analysis.
- *Prescriptive* - Models, where the state or subject of a system is to be realized. This is used to describe a system that is to be realized and can be applied during constructive processes or runtime evolution, such as in self-adaptive systems.
- *Predictive* - These kinds if models is used to predict information that has not yet been measured. These models can be used for i.e., analysis using Petri nets, simulations, and machine learning with neural networks.

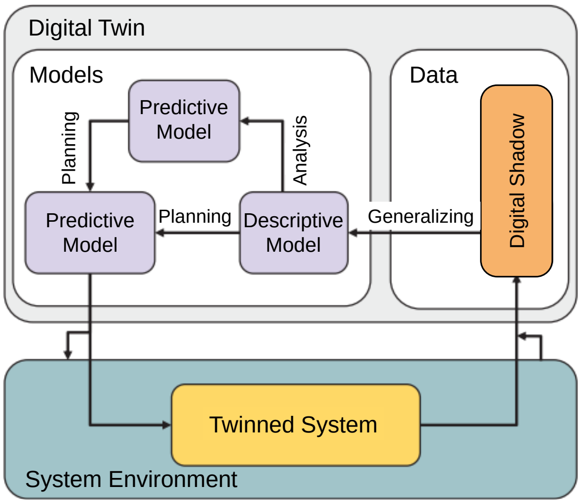

Figure 4: Kinds of models and their respective purpose [98]

We assigned the combination of purposes to each publication. For example, a single publication might describe a DT that leverages both descriptive and predictive models.

RQ-2.3 - DT Software: Following the 5D model DTs, we expect them to comprise software that manages artifacts related to all five dimensions. This includes database software that maintains data obtained from the actual system, model management software that deals with its internal models of the twinned system, communication software that interacts with the system, and additional software for the DT's services, such as visualization and analyses. Additionally, we include the most prominent types of software identified in the most comprehensive DT survey to date [92].

Consequently, we expect the following kinds of:

- *3D Visualization Software* - Software that focuses solely on visualizing and describing machine tools through automated data transformations. Examples include software for building 3D structure models of machine tools, such as Windows Control and Automation Technology (TwinCAT) by Beckhoff or Vertex by Amazon Web Services (AWS).
- *Data Management Software* - Software that creates, retrieves, updates, and deletes (CRUD) data from or about the twinned system, e.g., database software.
- *Model Management Software* - Software for CRUD activities on the DT models of the

twinned system, such as parsers or code generators.

- *Communication Software* - Software that interacts with the twinned system (e.g., via OPC UA) or with other systems in the DT's environment (such as a manufacturing execution system (MES) or an enterprise-resource-planning (ERP) system).
- *Programming Languages and Frameworks* - Such as frameworks for DTs, and the architecture of DTs. Examples of possible answers include general-purpose languages for building frameworks, databases, and network interfaces.
- *Simulation Software* - Software used to predict the behavior of the machine tool. Possible answers include MATLAB and graphs to describe the behavior.
- *Other Software* - Specific software that does not fit into other categories.

One publication may describe using multiple software tools for engineering or operating DTs.

RQ-2.4 - DT Visualization: A DT can be visualized in different ways to show the behavior of a machine tool [92]. Therefore, it is interesting to know the software methods and tools used for visualization. The following describes the classification of the different visualization methods, which a DT can have:

- *3D Visualization* - This classification is used when no specific software or detailed description of 3D visualization is provided. Three-dimensional visualization is the process of creating graphical content that represents objects, scenes, or data in three dimensions. When a more detailed description of the visualization is provided, the following clusters are used.
- *3D Visualization: CAD* - Computer-aided design (CAD) refers to the use of digital design software to create detailed 2D or 3D models of physical assets. These CAD models serve as foundational blueprints for a DT, providing accurate geometric data.
- *3D Visualization: Mixed Reality* -Mixed reality visualization, in the context of DT, refers to technology that blends the physical and digital worlds. Through devices such as augmented reality headsets or mixed reality glasses, users can see and manipulate the DT superimposed on the real-world environment. This enables enhanced analysis, decision-making, and training by visualizing virtual data alongside physical objects.
- *3D Visualization: Simulation* - A graphical representation of how a physical asset or system behaves under various conditions within a virtual environment.
- *3D Visualization: Unity* - Unity is a development platform for creating, visualizing, and interacting with DTs of physical assets, systems, or environments..
- *3D Visualization and Dashboard* - A combination of a 3D visualization and a dashboard.
- *Dashboard* - A dashboard is a user interface that provides a real-time, comprehensive overview of the virtual representation of a physical asset, system, or process.

RQ-2.5 - DT Composition: Efficient reuse is a major driver of software success. We reuse software in many ways, ranging from small parts (e.g., individual modules or classes) to larger parts (e.g., libraries or frameworks) to complete applications (e.g., virtualized or distributed via app stores). All of this reuse is based on composition, such as merging code, importing library functions into a class, or installing downloaded artifacts on a target platform, like Docker or an operating system. Sustainable engineering would also benefit from the ability to reuse and compose one DT with another [100, 122]. For example, one could compose the DT of a factory from the DTs of the product lines, which are composed from the DTs of the individual stations [103]. These stations are composed from the DTs of their sensors, actuators, and computing units. Therefore, we investigate whether the DTs presented in our corpus support either or both of these mechanisms.

- *Modularization* - Provision of stable interfaces that support reuse despite internal evolution; and
- *Composition* - Providing systematic means for merging, integration, linking, or similar.

RQ-2.6 - DT Evaluation Maturity: The maturity of the evaluations presented in a corpus may indicate the maturity of the field. If the evaluations are more often on lower technology readiness levels (TRLs) [108], this might suggest a more theoretical research area in which the time from a contribution's presentation to its implementation is longer. Consequently, we analyze the maturity of the evaluations presented to determine how close the presented DT technologies are to being deployed on the factory floor. Due to limitations of size or confidentiality considerations, publications rarely provide fully detailed evaluations. Thus, a precise estimation of evaluation maturity is rarely feasible. To accommodate this, we classify evaluation maturity as follows: Each publication is assigned to a single TRL range. See the brackets for details.

- *Proof of Concept* (TRL 1-3) - This includes evaluations in which at least the basic principles of the DT research can be observed and at most an experimental proof of concept is reported.
- *Technology* (TRL 4-6) - This includes evaluations where DT technology is at least evaluated in a laboratory context at a minimum and in a relevant environment at most.
- *System* (TRL 7-9) - This includes evaluations in which at least one DT prototype is demonstrated in an operational environment.

RQ-3. How are digital twins connected and how do they communicate?

RQ-3.1 - Vertical Connectivity: Communication between the DT and its physical counterpart is investigated. This communication involves sending data from the DT to influence the physical system and receiving data to update the model of the twin. Understanding the direction and nature of this data exchange is essential for evaluating the functionality of the DT and its role in optimizing the performance of its physical counterpart. It is important to determine whether the twin can actively send and/or receive data from the physical twin.

The Asset Administration Shell (AAS) [145] was designed to digitally map real assets in production. It is a concept that stores and provides all relevant information regarding the asset over its life cycle. The AAS can be categorized as passive, reactive, or proactive. A passive AAS is a static file, whereas a reactive AAS can receive data through a predefined interface. The proactive AAS can communicate with other systems and AASs autonomously [90]. Therefore, this study investigates whether the papers describe if a DT is capable of receiving data from the physical twin, and whether it is capable of sending data back.

RQ-3.2 - Horizontal Connectivity: DTs of machine tools are part of a larger infrastructure that may require them to connect to other systems in addition to their own. These systems may include computing clusters for complex machine learning applications, manufacturing execution systems, or central data stores for operational data. To determine which kinds of systems DTs of machine tools are often connected to and the technologies used for this connection, we analyzed the corpus. Potential answers to this question cannot be defined in advance, as a wide variety of higher-level systems can be used.

RQ-3.3 - Real-time Capabilities: Real-time capabilities play a significant role in the context of machine tool control. To safely and synchronously move multi-axis systems, real-time calculation of the controller itself and real-time communication between the controller and the involved field devices (i.e., sensors and actuators) are necessary [86, 88].

If DTs interact with machine tools, it is interesting to consider whether they are also capable of operating in real time, in terms of both computation and communication. Therefore, this study investigates whether the papers' publications describe:

1. *Real-time Communication* - Is the communication between the DT and the twinned system real-time capable?
2. *Real-time Computation* - Is the computation of the DT in real-time capable. Therefore, the DT can provide deterministic results.
3. *Real-time Implementation Details* - How are real-time communication and real-time computation realized?

5 Analysis

Vertical analysis provides quantitative results for all research questions. Answering these questions does not require considering other research questions. The following subsections present the results of this analysis. However, as not all research questions could be answered with sufficient significance or unambiguously based on our corpus, the Discussion briefly revisits observations and potential insights into these research questions.

RQ-1.1 - DT Counterpart: The vast majority of the detected DTs describe stations (58, 75 %), while only a few describe technical systems (12, 16 %). DTs of control units (4, 5 %) and products (3, 4 %) are even less common in our corpus. Not a single DT is included for field-level devices, enterprises, or the connected world. The situation regarding **RQ-1.1** can be explained by the strict focus of this study, which is highly biased by the concentration of publication on machine tools. Machine tools are prime examples of stations in the RAMI 4.0 [107] framework. Considering multiple machine tools leads directly to a technical system.

RQ-1.2 - DT Purpose: The majority of the works (28, 37 %) stated that the purpose of the DT was to improve quality [10, 38, 40]. In contrast, cost savings (4, 5 %) and time savings (5, 7 %) were mentioned less frequently. However, combining cost and time savings is the second most common purpose (10, 13 %) [4, 23, 30]. Figure 5 shows these findings.

Overall, a quarter of all works state no purpose or a purpose other than cost, quality, or time [24, 61, 69]. However, many economically driven production technologies ultimately come down to costs. Surprisingly, the majority of works state quality as their purpose.

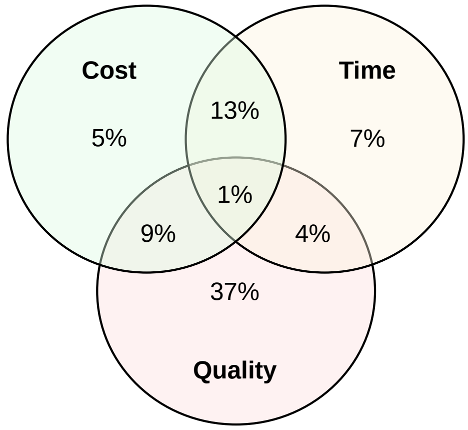

Figure 5: Venn diagram of the identified purposes: a total of 18 (24 %) of the papers do not specify a purpose at all.

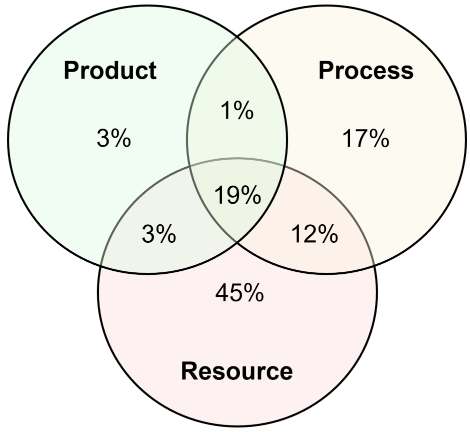

Figure 6: Venn diagram of the kinds of entities represented by the DTs according to the PPR schema

RQ-1.3 - Product-Process-Resource Categorization: The analysis of product process resources shows that the majority of resources DTs represent resources (35, 46 %). This phenomenon can be attributed to the predominant focus of research on DTs of machine tools, which also explains the observed quantity. The virtual absence of product twins is also noteworthy, accounting for 2 (3 %) of all instances. This finding indicates that the primary focus thus far has been on the process (13, 17 %) and the resource, accounting for nearly three-quarters of the findings (57, 74 %). The data of the specific clusters is illustrated Figure 6.

To obtain more information about the product in question, it is recommended that you conduct your research exclusively within the machine tool domain. However, note that this would require a significant investment of time and resources.

RQ-1.4 - Production Process: Of the analyzed papers, 38 focused on representing the production processes of DTs of machine tools. The examination shows that the majority of these studies (30,

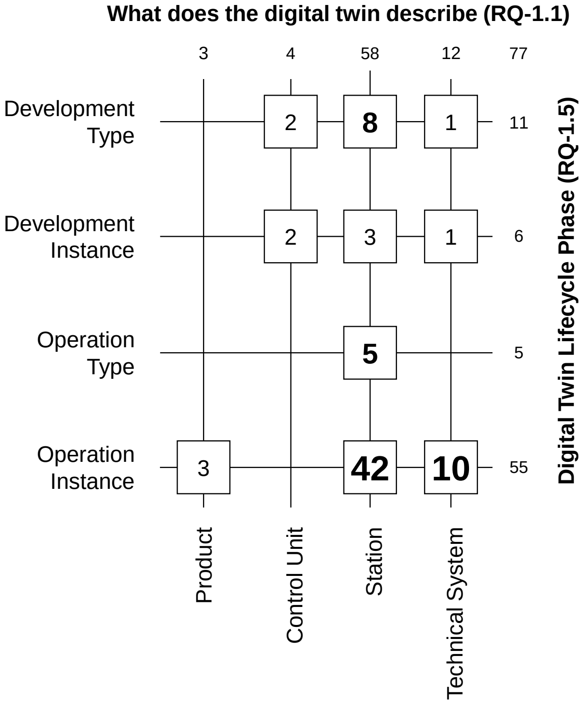

Figure 7: Juxtaposition of DT life-cycle phase according to RAMI 4.0 and corresponding hierarchy level

79 %) specifically address the twinning of milling processes. This dominance suggests a significant research interest in developing and refining DTs for milling, likely due to its widespread application in manufacturing. Three of the considered articles did not specify the production process, indicating a general approach to DT development. Additionally, the literature also covers other processes, such as grinding (2x), die casting (1x), drilling (1x), knife-cutting (1x), punching (1x), splitting (1x), and transmission (1x). Therefore, we can see that the focus of DT development is milling. A significant number of milling machines and processes are given particular attention.

RQ-1.5 - DT Life Cycle Phase: This research question explores which life-cycle phases the DTs represent. Generally, it is possible for a single DT to be used in multiple phases. However, only one DT was classified in both instance-related life cycle phases; all other DTs belonged to a single phase only, that is, this question produced 77 answers. According to the available data, instances are significantly more frequently included in DTs of the corpus (61, 79 %) than types (16, 21 %). However, there was a shift in the phases from type to instance.

The majority of type-DTs (11, 65 % of the 16 publications mentioning it) refers to the development phase of the type; a minority refers to the deployment phase. (5, 35 % of the 16 publications mentioning it). For instance, this relationship is reversed. Only a few instances-DTs (6, 9 %) refer to the development phase; most refer to the deployment phase of the instance (55, 72 %).

As the development of a machine tool is based on the instance and operation takes place on the type, the resulting data corresponds to the authors' expected values. It also seems plausible that the deployment of the type and development of the instance are correlated, as the phases are directly interlinked. In summary, we found that most of the DTs refer to the operating phase of the machine tool (55, 72 %) while earlier phases are mentioned significantly less common (22, 29 %). This is also reflected in the number of papers that consider virtual commissioning, which is a part of the development life-cycle.

The visualization of **RQ-1.1** and **RQ-1.5** and their classification within the RAMI 4.0 framework are presented in Figure 7. For projection into the three-dimensional RAMI 4.0, the tier is assigned to the information layer.

RQ-1.6 - Virtual Commissioning Configuration Type: The large majority of the analyzed papers did not describe virtual commissioning. Only 17 (22 %) papers addressed virtual commissioning as a use case for a DT. Within virtual commissioning, the focus was on model-in-the-loop (8, 11 %) [18] and hardware-in-the-loop (6, 8 %) [3] simulations, while only 3 (4 %) papers describe a software-in-the-loop configuration [21] for virtual commissioning.

This analysis shows that the majority of the analyzed papers do not use the term "digital twin", which is still used in practice for many different things despite the many attempts at standardization in connection with virtual commissioning.

RQ-2.1 - DT Constituents: Overall, only 67 out of 76 publications detailed the constituents of

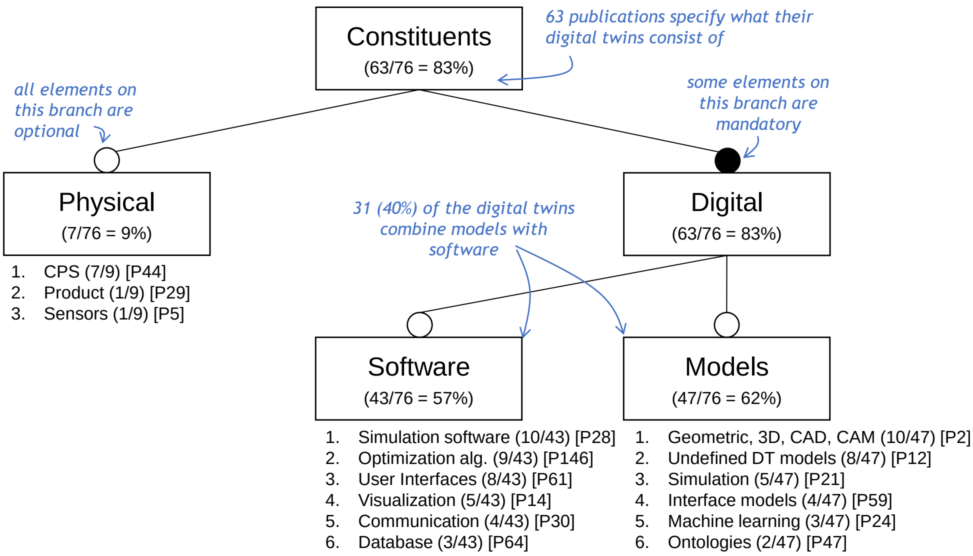

Figure 8: Constituents of DTs are most often models and software to represent and investigate the behavior of the twinned system (multiple mentions possible).

the presented DTs. Where specified, DT constitutes are primarily models (47, 62 %) and software (43, 57 %), though some publications consider physical elements to be parts of the DT (7, 9 %).

The most popular model types represent spatial information, e.g., 3D, CAD, and CAM models (10, 13 %), which is followed by undefined DT models (8, 10 %), and by simulation models (5, 6 %). The category of undefined DT models encompasses all models that were not further detailed, such as "cyber model" [20] or "model layer" [51]. Other important types of models include interface models (e.g., OPC UA information models), machine learning models, and knowledge models (e.g., ontologies). The DTs include software that focuses on simulation (10, 13 %), optimizing the behavior of the twinned system (9, 12 %), and user interaction (8, 10 %). This is followed by visualization software in 2D and 3D (5, 6 %), communication (4, 5 %), such as OPC UA or MTConnect, and database software (3, 4 %).

Models and software seem to be essential to DTs, and most combine both to provide DT functionalities, as there are no DTs without models or software. However, some DTs also appear to comprise physical elements. Regarding software, the main concerns seem to be simulation and behavior optimization of the twinned system, which is in line with the prevalence of 3D CAD, CAM, and simulation models in this context. Additionally, the fact that only three DTs feature a database suggests that either the obtained data does not persist, or the inclusion of databases in DTs has become commonplace. The lack of description of communication software might suggest the same for connectivity. Perhaps using solutions such as MTConnect, OPA UA, or Message Queuing Telemetry Transport (MQTT) has become so common that most authors no longer consider it necessary to discuss these solutions. This could also explain why OPC UA information models are rarely mentioned (4 times only).

RQ-2.2 - DT Models: A closer look at the models used in DTs reveal that a total of 81 models were used in 64 of 76 publications, as depicted in Figure 9. The purpose of these models was also examined. In our corpus, 57 publications mentioned at least one of these purposes. A substantial number of models (41, 50 %) were used to represent the physical counterpart from a structural point of view. Among the 41 structure models, 3D models [28, 45, 68] (5, 12 %), and CAD/CAM models [8, 27, 53] (8, 20 %) were the most popular. Subsequently, OPC UA models were found in the literature [32, 27, 24] (4, 10 %). More than half consisted of other models (24, 58 %). More precisely, these models included the Automation Markup Language (AutomationML) [3] (1, 2 %), geometric models [33, 59, 64] (3,

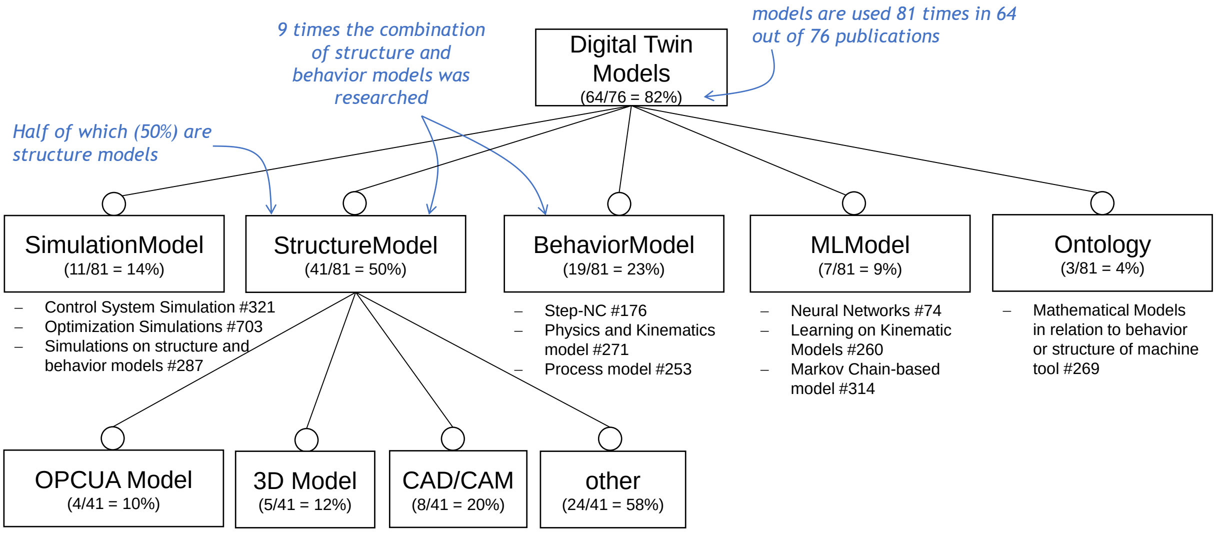

Figure 9: Models can be further divided into categories, which realize a property of a digital twin, such as simulation capability or visualization of the structure in combination with a behavior.

7 %), and domain-specific models [15, 66, 72] (12, 30 %). For example, domain-specific models predict the grinding and wear status models of both the machine and the workpiece, as well as data and information models (i.e., Modellica, Functional Mock-up Interface, Finite Elemente Methode) [21, 63, 4] (3, 7 %). Structural models are used in 32 papers to describe the characteristics of a system. Furthermore, 16 articles research an extension to a predictive model of valid configurations or states. However, it is notable that only 5 studies further extend structural models in conjunction with software. The less popular ones are behavior models (19, 23 %), which provide information on processes [42] or physics and kinematics [33, 34, 44, 48, 76, 40, 62]. These models describe potential movements or actions that can be taken from a given state, as discussed 13 times in the literature. In contrast, a projection of the system's foreseeable states of the system is presented for prediction purposes 10 times in the literature. Unlike structural models, behavior models are never used for prescriptive purposes. Simulation models were present in (11, 14 %) cases for predictive purposes. The final two categories are for one machine learning models (7, 9 %) with trained neural networks [36], and weighted models on kinematics or Markov decision chains [1]. Similar to simulation, the focus is on prediction and description for prescriptive purposes. The least researched are ontologies (3, 4 %), which attempt to relate mathematical [30, 37] and kinematic models of the DT to the behavior or structure [9, 68] of a machine tool. Thus, an ontology commonly has descriptive, prescriptive, and predictive purposes.

Reinforcing the previous assumption, we can now see that there seems to be a trend toward viewing the models functionally. Each model serves a specific purpose, such as visualization or machine learning [92]. Additionally, there appears to be an increasing tendency to develop research tailored to the particular needs of each application. This is particularly evident in domain-specific solutions for structural DT models (12 occurrences). Additionally, research on simulation, behavior, and machine learning tends to focus on specific technologies or solutions, rather than on generalizable conclusions.

RQ-2.3 - DT Software: The software or tool used for developing and managing DTs is referenced in 38 (50 %) of 76 publications. This information is often absent from publications that focus on the results rather than the methodology. Although large clusters are visible among the tools used to develop DTs, it is notable that the number of intersections between them is relatively limited. Overall, 54 software tools were used in 38 publications. The largest group consisted of programming languages and frameworks with a total of 13 (24 %), such as Java [1] or C++ [8, 70],

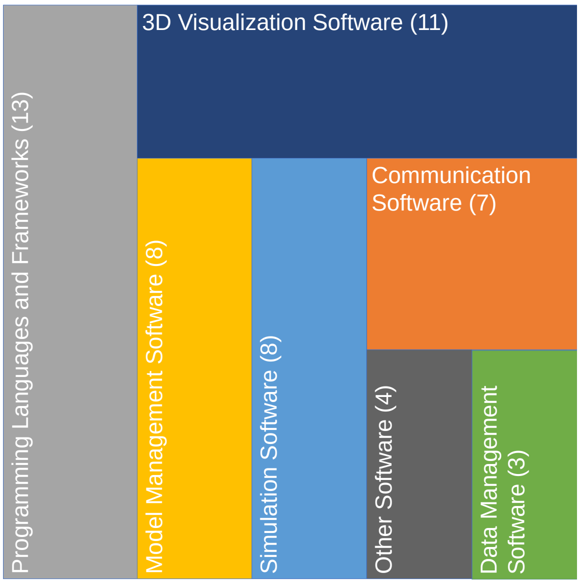

Figure 10: Software used for engineering DTs.

as well as and frameworks, such as Dynola [4], or model libraries [64]. Subsequently, 3D Visualization Software was leveraged 11 (20 %) times. Unity is a commonly used platform for 3D visualizations [26, 28, 48]. Simulation software was used in 8 (15 %) cases. Additionally, simulation software is often built upon existing 3D visualization frameworks, such as SolidWorks [59, 12] and Unity. The same is true for model management software, which manipulates models of the DTs. In 8 (15 %) cases, a framework such as MATLAB [32, 37, 59] was used to create and update models. Another aspect to consider is the communication software used in 7 (14 %). Communication software commonly uses a framework based on an industrial standard, such as OPC UA [24, 44, 66], for communication. Finally, other software, such as TwinCAT [55],graph representation [30], or virtualization software [32, 71], collectively comprise 4 (7 %) of the software used. In contrast, data management software is employed in only 3 (5 %) cases [10, 24, 71], s the interpretation of data is connected to an underlying model, and the choice of database does not seem to be an important factor.

The widespread use of MATLAB and SolidWorks, as well as other commercial tools on top of Unity, demonstrates technological readiness. However, these tools yield unreplicable results and ad hoc software for DTs. This reinforces the idea that each study focuses on a specific aspect, which limits its generalizability.

RQ-2.4 - DT Visualization: Most of the analyzed publications do not describe or mention any visualization methods for their DTs (27, 36 %). Furthermore, 10 (13 %) do not explicitly employ visualization. One potential explanation is that various types of DTs do not need visualization. Additionally, the analyzed publications 12 (16 %) employed a visualization method with a 3D visualization; however, they did not specify the software or tools used. The most frequently referenced 3D visualization method is Unity, with 8 (11 %). This prevalence can be attributed to Unity's capacity for seamless integration with diverse simulation tools, facilating the straightforward incorporation of a visualization tool. Additionally, its inherent physics enginemakes it an optimal choice for physics-based simulations.

Visualization methods such as 3D simulation are commonly used to visualize a DT. However, they are not widely used in the field of machine tools. Only 45 papers feature a visualization of their DT.

RQ-2.5 - DT Composition: Composition is the topic of only a few publications 12 (16 %) in our corpus. Where this topic is discussed, the DTs consist of modules for analysis, decision making, information extraction, maintenance, scheduling, simulation, and sending commands to the actual system [25, 32, 49], which, essentially, resemble the functional entities suggested in ISO 23247 [110] (cf.. Figure 11). However, even fewer publications in our corpus discuss composition. Only 3 (4 %) of the publications explicitly discuss the composition of DTs at all. These DTs are either logically decomposed into decoupled layers [28] Neither their interfaces nor the effect of composition on the DTs's behavior is elaborated on. Overall, DTs consist of software components, and reuse is vital for the efficient creation of software. However, this may not yet be relevant for DTs of machine tools. This may be because the DT of a machine tool is always considered as a whole entity, or because there is a lack of simpler twins from which the DT could be composed.

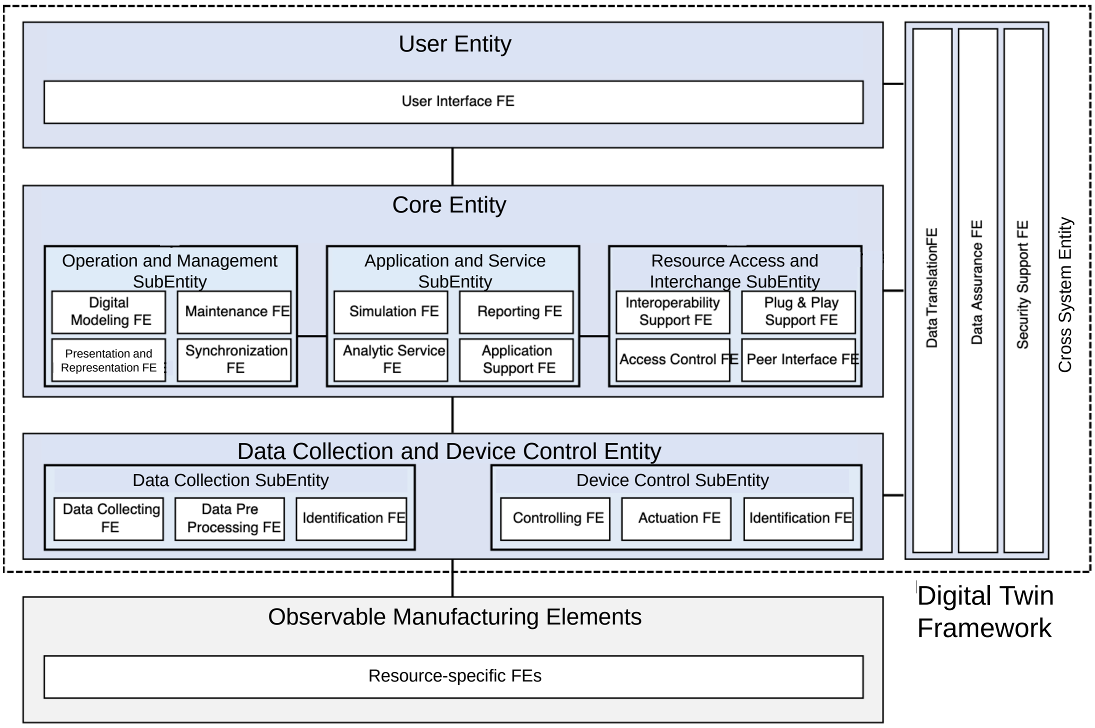

Figure 11: Suggested DT modules, called "functional entities" (FEs), of ISO 232477 [110]

RQ-2.6 - DT Evaluation Maturity: In our corpus, only 73 (95 %) of the publications reported on an evaluation. Of those, 38 (49 %) reported on evaluating proofs of concept (TRL 1-3), 33 (43 %) are reported on evaluating DT technologies (TRL 4-6), and only 2 (3 %) reported on evaluating systems (TRL 7-9). Thus, proof of concept evaluations and technology evaluations are almost evenly distributed, together making up 71 (92 %) of the publications.

Indeed, the number of reported evaluations at TRL 4-6 is higher than that reported in a general mapping study on DTs across all domains [92]. In the latter study, only 22 % of the evaluations were identified at this TRL level, whereas 33 (43 %) of the publications in our corpus report evaluations at this level. This suggests that research on DTs for machine tools is generally more mature than the research on DTs.

RQ-3.1 - Vertical Connectivity: Vertical connectivity allows the DT to communicate with its Physical Twin. To replicate the state of a Physical Twin, the DT must be capable to receive data from its counterpart. In addition to adapting the physical entity, the DT must be capable of sending data to it. Of the 76 papers considered, 53 (70 %) papers describe the DT's ability to receive data from its original. However, only 28 (36 %) of the DTs were capable of sending data to the physical counterpart.

This result shows that the definition of a DT is ambiguous. A DT must receive data from the original and be able to influence it. According to this definition [117], if the original cannot be influenced, then it is a digital shadow.

RQ-3.2 - Horizontal Connectivity: Most of the publications 73 (95 %) in our corpus do not explicitly state whether the DT can communicate with systems other than the twinned actual system. Of the 3 publications that provide this information, the DT can connect to various systems, including product data management systems [24], simulators [14], and arbitrary OPC UA recipients [27].

Overall, connectivity between DTs and related systems is not a significant issue for machine tools. This may be because the context of their use (e.g., factories) follows well-structured communication hierarchies that do not require the DT to interact or are not the focus of research in this field. The communicating DT is still a vision of the International Digital Twin Association (IDTA)[5] coined as the Type 3 Asset Administration Shell [105], it may hint at the latter assumption. Future studies on DTs for machine tools may answer this question.

RQ-3.3 - Real-time Capabilities: Real-time communication and calculation are essential for DT applications and are often necessary for integration into industrial environments. Many papers claim to support real-time communication (37, 49 %) [27, 29, 45] and real-time computation (28, 37 %) [26, 38, 44]. However, rarely is it explained how this is realized. Communication is most likely to be discussed in detail. IP-based protocols from IT are the most common choice (36, 47 %) [33, 45, 50]. Many of these studies use IT protocols with an overlaid data model. The following technologies were described among the papers: Beckhoff Automation Device Specification (ADS) (1, 0.8 %) [67], fanuc FOCAS (4, 3.3 %) [21], 5G (1, 0.8 %) [39], MTConnect (1, 0.8 %) [71], and OPC UA (6, 4.9 %) [37, 35, 67, 71].

Remarkably, a significant proportion of papers claiming to support real-time functionality failed to provide implementation details. This suggests that not all of these implementations are capable of real-time operation, as is the case with fieldbuses in production technology. IT protocols, in particular, are often not deterministic. Therefore, real-time is often equated with the terms "live" or "in operation." This is an acceptable practice because not all applications require deterministic real-time communication or calculations. However, the frequent use of this term is questionable.

Further Insights

In addition to answering our research questions, we gained further insights from our corpus. This section outlines the findings of this study.

Although products are often defined in the context of product creation using a CAD model [113], no DT represents a model of the product in the context of the evaluation. Based on this, and in accordance with the DT definitions in this paper, it can be concluded that a pure product model is not referred to as a DT.

We have found that predictive and prescriptive models are rarely used without descriptive models, only shown in 11 (15 %), whereas all other DTs employ descriptive models. Also, DTs that leverage models seem to require descriptive models (**RQ-2.2**) as a foundation for predictive and prescriptive models.

Analyzing the use of visualization technologies for DTs (**RQ-2.4**) in the context of the presented evaluation maturity (**RQ-2.6**) shows that despite having similar numbers of evaluations on TRL 1-3 and TRL 4-6, the use of 3D visualization declines from TRL 1-3 to TRL 4-6. This could indicate that 3D visualization is used in the early phases to develop DTs, but it loses relevance in the context of deployment because its purpose of securing the development process is fulfilled.

For research question **RQ-3.3**, we aimed to examine the nature of the real-time capabilities of the papers. A total of 40 (52 %) papers claim to support real-time communication, and 29 (38 %) claim to support real-time calculation but only 18 (24 %) papers explain how communication is implemented, and 11 (14 %) explain how calculation is implemented. The problem with the term "real-time" is that it is often used interchangeably with terms such as "live" or "operating" and "connected to a real machine". Few studies have implemented deterministic real-time communication and calculation as is common in industrial automation, e.g., fieldbuses. Most use cases do not actually require real-time capabilities, so it is perplexing that this claim persists. This can also be seen in the combined analysis of questions **RQ-3.1** and **RQ-3.3**, which shows that if the DT is capable of receiving data from the PT, the corresponding papers claim that the communication is also real-time capable (34, 44 %).

6 Summary

This section summarizes the answers on the three main research questions. The results are strongly emphasized. The detailed presentation of the results is provided in Section 5.

[5]IDTA website: https://industrialdigitaltwin.org/en/.

RQ1. What does the digital twin describe and when is it used?

We found that DTs primarily describe resources (**RQ-1.3**) that are realized by stations or their combination in technical systems (**RQ-1.1**) to improve quality (**RQ-1.2**). As machine tools are prime examples of stations in the RAMI 4.0 [107] framework, we assume that primarily individual machine tools are described. On the process side, the main focus is on milling (**RQ-1.4**), which is not surprising as milling is the traditional machine tool process. Most of the DTs are utilized within the operating phase of the machine tool (**RQ-1.5**) while the utilization within earlier phases is, as, e.g., for virtual commissioning (**RQ-1.6**), is significantly less common. Hence, the use of DTs in early life-cycle phases, thus reducing costs and development time might be a gap in research worthwhile to investigate

According to the data situation, DTs mainly map resources, not products or processes. Simultaneously, DTs are mainly used to improve quality. Whether product or process quality is to be increased by mapping resources in DTs, or the concept of quality in the area of resources is to be interpreted in some other way, remains open. Therefore, further research has to be conducted to unambiguously answer the purpose of DTs.

RQ2. How are digital twins developed?

The question of how DTs are developed can either be answered by defining the structure of the DTs at runtime, or by examining the development phase of the DTs. Structurally DT comprise, if specified, models and software components (**RQ-2.1**). Typical models, considered to be part of the DT during runtime, are spatial information, e.g., CAD or CAM models, simulation models, interface models, machine learning models, and knowledge models (**RQ-2.2**). Software components in DTs typically address simulation, system behavior, or user interaction (**RQ-2.3**). In contrast to our expectations, AI models and ontologies are used rarely. Likewise, the visualization of DTs is rarely addressed (**RQ-2.4**) as well. Where explicitly addressed, 3D virtualization is suggested; if specified the implementation technology is Unity. The data on DT composition in the corpus is sparse (**RQ-2.5**). However, if addressed, ISO 23247 [110] is claimed to be implemented. Overall, composition and modularity of DTs yields several opportunities for future research to ease the development of DTs through systematic reuse of DTs and their parts. However, while lack such reuse techniques, the analysis of evaluation maturity suggests that the DTs developed for machine tools are more mature than DTs reported on in scientific literature in general (**RQ-2.6**), which might be due to the focus on a single kind of system or due to the domain often producing results being closer to industrial applications than science in general.

RQ3. How are digital twins connected and how do they communicate?

The connectivity of DTs can be divided into horizontal and vertical connectivity. Vertical connectivity allows the DT to communicate with its Physical Twin, horizontal connectivity allows the DT to communicate with systems other than the twinned actual system. Vertically, most of DTs feature a unidirectional connection that allows the DT to receive data from the physical system, some of DTs feature a bidirectional connection that also allows the DT to send data to the physical system (**RQ-3.1**). The horizontal connection of DTs, however, is hardly addressed in the corpus (**RQ-3.2**). This lack in addressing horizontal communication is consistent with the fact that the papers mainly address individual machines or systems (cf. **RQ-1.1**). An orthogonal analysis of vertical connectivity and horizontal connectivity does not allow any reasonable conclusion about the overall connectivity of DTs, presumably based on the small amount of data available to answer**RQ-3.2**.

Communication is widely based on IT protocols at a higher level of the OSI model. The ability to communicate in real-time is attributed to just under half of the DTs considered (**RQ-3.3**). However, the description of how real-time communication is realized is largely missing.

Horizontal connectivity and real-time capabilities of DTs demand additional research. In accordance with the rated work, i.e., [117], according to which objects without a connection to the physical counterpart are referred to as models whereas objects that are limited to receiving data from the physical counterpart are referred to as digital shadows, one can conclude the question whether all systems referred to as DT within the corpus should be considered as such. The concrete answer to the question depends on which DT definition the reader applies.

7 Research Challenges

7.1 DTs of Products

According to the vision of Industry 4.0, smart products know how they need to be constructed and communicate this information to the stations processing them. Consequently, a DT of such a product, capturing its current and future states with suitable models that are updated as the actual product is being manufactured, might provide valuable information and services regarding the production process. However, our corpus does not suggest that such smart product twins exist in the context of machine tools. We only identified three publications that describe DTs of products. If the vision of smart products together and their DTs becomes a reality, this demands additional research on the data, models, relations, and services to realize such DTs.

7.2 Real-Time Capabilities

Our investigation has shown that most approaches are based on a communication with IT protocols at a higher level of the Open Systems Interconnection (OSI) model. For instance, data is aggregated and cached for this purpose. For some use cases, such as the ones described, this approach is effective. However, if DTs are intended to support and improve production systems at all levels in the future, they must be capable of deterministic real-time performance. This would allow for the optimization of closed-loop control tasks and the implementation of safety-critical use cases, such as collision avoidance [115]. Furthermore, a higher degree of real-time capability increases the importance of DTs as the technological backbone of smart manufacturing.

7.3 Virtual Commissioning

Virtual commissioning is a method originating in automation technology used to test control systems before real commissioning begins. The term DT was only merely used for describing virtual commissioning. However, combining simulation technologies and DT to optimize plant operation is a relevant goal for achieving the vision of Industry 4.0. Virtual commissioning models support real-time capabilities and are used in engineering applications, which is why they are relevant to achieving the vision of Industry 4.0. Methods must be developed to transfer these models and software solutions from virtual commissioning to operations.

7.4 Horizontal Connectivity

DTs are part of a larger ecosystem regarding developing and operating machine tools. As such, they could benefit from interacting with development systems (such as IDEs, AI co-pilots, and simulators) as well as from interacting with operation systems (e.g., ERP, and MES). This requires well-defined interfaces between the DTs and these systems. The findings of our study suggest that such interfaces are not yet in use, at least for machine tools. The Industry 4.0 Language [145] could become the lingua franca for this purpose. Further research on such interfaces could also foster the reuse of DTs in different contexts by encapsulating information about the actual system that is independent of specific applications. This would allow them to easily connect to other systems that provide application-specific information through a dedicated interface.

7.5 Composition and Modularity of DTs

According to the publications in our corpus, DTs are usually engineered in a monolithic fashion. This approach is inefficient and prevents scaling up the use of DTs. Reusing software and software models [99] is an important means of reusing solutions and knowledge between software projects and, DTs. Due to their multiparadigmatic nature, which combines data, models, and software, systematic reuse methods are lacking [122]. Addressing this lack of methods is necessary to make DTs accessible to everyone outside of research laboratories, especially small-to-medium enterprises.

8 Threats to Validity

Our study is subject to threats that affect its validity. In the following section, we analyze and classify these threats according to [147] as construct, internal, external, and reliability validity. Construct validity refers directly to a study's overall design, such as a search query or evaluation criteria. External threats restrict the generalizability of a study, while internal validity refers to the specificity of the factors that influence the conclusions drawn by the readers. Reliability describes how trustworthy the study's results are.

Regarding threats to the construction of this mapping study, there are many similar yet distinct terms for describing DTs, such as digital shadows, virtual twins, etc. While some publications have extensively distinguished between these terms, others use them interchangeably. To ensure accurate mapping, we treated these terms as separate concepts, following the definitions of [117] by default. However, if an investigated publication switched the wording while clearly referring to the DT, we followed the paper's intellectual road map and considered these as synonyms. This approach yielded accurate analysis results for the included papers. In contrast, publications that used only different terms (e.g., constantly mentioning virtual copies without including the term of a DT) could not be recognized in this study, because it is impossible to extract whether the authors refer to the DT concept or explicitly distinguish it from it. This topic could be addressed in a future study that explicitly includes all potential synonyms, thus covering a broader yet less precise scope.

A significant challenge to the validity of this study using the keywords "digital twin" and "machine tool" is the risk of incomplete coverage due to inconsistent or evolving terminology across studies. It is important to note that research which is relevant to this subject may be overlooked if it employs alternative phrases or focuses on adjacent technologies without employing these terms explicitly. Moreover, the interdisciplinary nature of the topic can result in fragmentation across domains, which can hinder the comprehensive capture of relevant literature. These factors may result in an incomplete study and potentially biased findings.

A further threat to construct validity arises from our exclusion criteria. During the initial screening of papers, we only considered titles, keywords, and abstracts. This procedure may have mistakenly excluded potentially relevant publications. Papers focusing on the machining process that address the machine tool in the body of the paper were discarded, as in [82]. To minimize this effect, we generally included papers for which we were uncertain, and only excluded those in the classification phase when they turned out to be irrelevant for our mapping study. Furthermore, we assumed that the relative conclusions drawn from this work remain valid even if individual papers are excluded because of the limitations of the methodology.

Since our work is based on a literature review, it is inevitably subject to publication bias. Primarily, more successful and positive reports on the topic have been published. This complicates the assessment of areas that are not positively affected. DTs, or for which applicable concepts and methods for constructing them are not applicable. Furthermore, there may be research and material outside of common research distribution channels, such as gray literature, that must be handled specifically [135]. Further work on the analysis of the current status of DT research could focus on gray literature.

We have used the search engines of leading scientific databases and libraries, SpringerLink, IEEE Xplore, ACM Digital Library, WoS, and Scopus, to search for literature. We intentionally excluded Google Scholar as a search engine, as it contains vast numbers of non-peer-reviewed publications (which would have been excluded during screening in any case). Moreover, we found that conducting the same search on Google Scholar from different accounts and/or networks lead to different results, thereby compromising replicability. Although this may negatively affect the external validity, it increases the reliability of search results.

Regarding internal validity, the publications differ significantly in the level of detail with which they explain DTs and their constituents. Authors often do not specify the exact system boundary of a DT, which impedes the precise mapping of relevant technologies. For example, it is often unclear whether a cloud system is an integral part of a DT or whether the DT merely uses it for communication. To obtain an unambiguous mapping, we generally decided on these cases in favor of the DT, attributing these properties and technologies to its realization. In addition, controversial issues have been discussed by the authors.

9 Conclusion

This article presents the results of a comprehensive and systematic mapping study on DTs for machine tools. We analyzed three main research questions and sub-questions to shed light on why, when, and how they are engineered and used with machine tools, as well as on the tools being used for their engineering and their communication capabilities. Our findings indicate that DTs for machine tools typically represent specific station types during operations and are primarily used for milling processes to enhance process or product quality. To this end, the DTs consist of models (CAD, simulation, etc.) and software (MATLAB, Unity, etc.) to operate on these models, analyze them in the context of data from the Physical Twin. Additionally, we found that software systems constituting DTs are largely engineered from scratch, without reusing previous DTs or DTs of parts of the twinned system. Despite this, the evaluation maturity of DTs for machine tools is comparatively high compared to findings from surveys on DTs in general. Many publications in our corpus consider DTs capable of real-time communication and/or computation; however, few specify how these capabilities are achieved.

Based on these findings, future research on the efficient use of DTs for machine tools could focus on bridging the perceived gap of making real-time communication and computation accessible for the engineering of DTs. Neither their horizontal connectivity nor reuse through composition has been adequately addressed.

Declarations

Corresponding author Andreas Wortmann (andreas.wortmann@isw.uni-stuttgart.de)

Author contributions All authors – Shengjian Chen, Carsten Ellwein, Lars Klingel, Rebekka Neumann, Jingxi Zhang, Oliver Riedel, Alexander Verl, and Andreas Wortmann – have contributed equally to this study.

Data availability

The data that support the findings of this study are openly available in DaRUS at https://doi.org/10.18419/darus-4542.

Disclosure of interest

Competing interests No competing interest to declare.

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