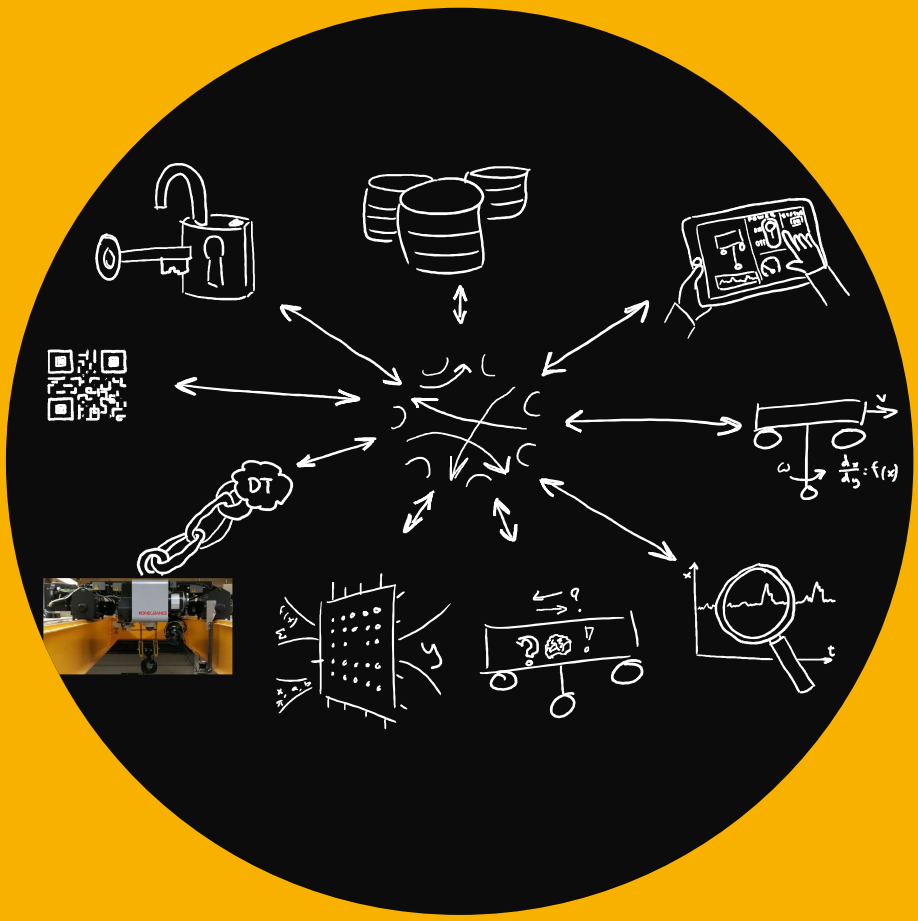
Mechanical Engineering

Discovering the Digital Twin Web

From singular applications to a scalable network

Juuso Autiosalo



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Discovering the Digital Twin Web

From singular applications to a scalable network

Juuso Autiosalo

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Abstract

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Abstract

Digital twins are virtual entities that are linked to real-world entities. Twins mirror their real counterparts and consist of features that are selected to serve the underlying use cases. Over the past decade, digital twins rose from an engineering curiosity to a concept praised by consulting agencies, offered by corporations, and pursued by governmental agencies. Digital twins are expected to bridge the gap between digital and physical worlds.

This dissertation set out to build machine design-focused digital twins for industrial products, specifically for an industrial overhead crane. However, during the work, it turned out that the existing tools and techniques did not allow the scalability required to create a twin for each manufactured product, suggesting that a more ground-up research approach was required. Hence, the latter part of the dissertation focused on initiating the development of fundamental digital twin technologies.

The four main results are a feature-based digital twin framework, a case study on practical digital twin development, preliminary *digital twin document* specification as a method for describing digital twins, and *Twinbase* as server software for distributing digital twin documents. 1) The framework presents a conceptual approach for building digital twins, consisting of features and connecting software blocks to build modular digital twins. 2) The case study describes lessons learned from developing a multi-component digital twin for an industrial crane in multiple teams and organizations. 3) A digital twin document enables the integration of twin components and acts as a master metadata source for a digital twin. 4) The open-source server software Twinbase allows twin owners to publish digital twin documents as effortlessly as possible, allowing rapid development cycles and innate collaboration.

The developed technologies will accelerate the creation and standardization of scalable digital twin entities. As a synthesis of the results, the dissertation introduces the *Digital Twin Web (DTW)* as an initiative for building a global network of digital twins. In the network, each digital twin is represented by a digital twin document. The structure of DTW is analogous to the *World Wide Web (WWW)*, consisting of servers and clients and leveraging open specifications. Key differences are the direct relation to the real world and readability for both humans and machines. Standardization of the digital twin document is seen as an imperative topic for future research. Other topics for standardization were identified as well, for example defining a transfer protocol for twin documents.

During the digital twin development, user-friendly Application Programming Interfaces (APIs) proved valuable resources, and also open-source software and open standards supported the development.

Keywords Digital twins, integration, open source, data management, metadata, Internet, cyberspace, cyber-physical systems, Internet of Things, Industry 4.0

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Tiivistelmä

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Tekijä
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Väitöskirjan nimi
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Tiivistelmä

Digitaaliset kaksoset ovat virtuaalisia entiteettejä, jotka on liitetty tosimaailman entiteetteihin. Kaksoset peilaavat todellisia vastineitaan ja koostuvat ominaisuuksista, jotka on valittu palvelemaan niiden käyttötapauksia. Viime vuosikymmenen aikana digitaaliset kaksoset nousivat insinöörien kuriositeetista konseptiksi, jota konsultointitoimistot ylistävät, yritykset tarjoavat ja virastot tavoittelevat. Digitaalisten kaksosten odotetaan yhdistävän digitaalisen ja fyysisen maailman välillä olevan kuilun.

Tämän väitöskirjan tarkoituksena oli rakentaa koneensuunnitteluun keskittynyt digitaalinen kaksonen teollisuustuotteille, erityisesti siltanosturille. Kävi kuitenkin ilmi, että olemassa olleet työkalut ja tekniikat eivät mahdollistaneet skaalautuvuutta kaksosen luomiseksi jokaiselle valmistetulle tuotteelle, joten tarvittiin perusteellisempaa tutkimusta. Näin ollen väitöskirjan jälkimmäinen osa keskittyi käynnistämään digitaalisen kaksosen perusteknologioiden kehityksen.

Neljä päätulosta ovat ominaisuuspohjainen digitaalisen kaksosen viitekehys, tapaustutkimus digitaalisen kaksosen käytännön kehityksestä, alustava määrittely digitaalisen kaksosen dokumentille ja *Twinbase* palvelinohjelmistona digitaalisten kaksosten dokumenttien jakeluun. 1) Viitekehys esittelee teoreettisen menetelmän digitaalisen kaksosten rakentamiseen, koostuen ominaisuuksista ja ohjelmapalikoiden yhdistämisestä modulaaristen digitaalisten kaksosten rakentamiseksi. 2) Tapaustutkimus kuvaa opittuja asioita siltanosturin moniosaisen digitaalisen kaksosen kehittämisestä usean tiimin ja organisaation kesken. 3) Digitaalisen kaksosen dokumentti mahdollistaa kaksosen osien integroinnin ja toimii perusmetatietojen lähteenä. 4) Avoimen lähdekoodin palvelinohjelmisto Twinbase mahdollistaa kaksosdokumenttien julkaisun vaivattomasti, mahdollistaen nopeat kehityssyklit ja luontaisen yhteistyön.

Kehitetyt teknologiat nopeuttavat skaalattavien digitaalisten kaksosten luomista ja standardointia. Väitöskirja esittelee digitaalisten kaksosten verkon (Digital Twin Web, DTW) aloitteena maailmanlaajuisen kaksosverkoston rakentamiseksi. Verkostossa jokaista kaksosta edustaa digitaalisen kaksosen dokumentti. DTW:n rakenne on vastaava kuin maailmanlaajuisen tietoverkon (World Wide Web, WWW), koostuen palvelimista ja asiakasohjelmista ja hyödyntäen avoimia määrittelyitä. Keskeisiä eroja ovat suora yhteys todelliseen maailmaan ja sekä ihmisten että koneiden luettavuus. Digitaalisen kaksosen dokumentin standardisointia pidetään välttämättömänä aiheena jatkotutkimukselle. Myös muita standardoinnin aiheita tunnistettiin, kuten siirtoprotokollan määrittäminen kaksosdokumenteille.

Digitaalisten kaksosten kehittämisen aikana käyttäjäystävälliset ohjelmointirajapinnat osoittautuivat arvokkaiksi resursseiksi, ja myös avoimen lähdekoodin ohjelmistot ja avoimet standardit tukivat kehitystä.

Avainsanat Digitaaliset kaksoset, integraatio, avoin lähdekoodi, tiedonhallinta, metatieto, Internet, kyberavaruus, kyberfyysiset järjestelmät, esineiden internet, Teollisuus 4.0

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Preface

This dissertation describes a journey from starting to develop digital twins with high hopes for the concept, finding out that it is not yet quite where we would like it to be, and beginning to build the basics of digital twins from the ground up. Luckily, the hardships led to the discovery of the Digital Twin Web approach. It seems that we have now gained a higher understanding of what digital twins are and should be and put it into a package that concretizes future development goals for digital twins. The future feels exciting.

For me, the journey was a true exploration into the worlds of science and digital twins. The journey was both lonely and full of people, as one would imagine for this kind of research topic. I hoped it would have been quicker, but I am glad I had the patience because now I feel I have achieved what I set out to achieve.

I would like to thank all the people who contributed to my dissertation project. Minna Lanz and Jari Kaivo-Oja pre-examined this dissertation, providing several valuable suggestions for enhancing the content. I also thank Jari for acting as an interdisciplinary opponent in the public examination of this dissertation. My supervisor Kari Tammi provided me with an appropriate mix of freedom, responsibility, patience, guidance, and support, allowing me to explore digital twins in the best imaginable ways.

Jari Juhanko, Pekka Nikander, and Josh Siegel were the de facto instructors for my dissertation work. Pekka introduced me to the world of cryptography and distributed ledger technologies, which are proving essential research topics for future digital twins. Josh welcomed me for a research visit to the United States, polished many of my skills by leading by example, and supported me in the unfortunate times of a global pandemic.

I joined the preparation of the DigiTwin project as a research assistant and somehow found myself in the role of a project manager. Valtteri Peltoranta from Konecranes accompanied me in project management in a way that I highly appreciate. Matti Lehto was a mentoring character for the project and pointed out the need for scalable digital twins in the

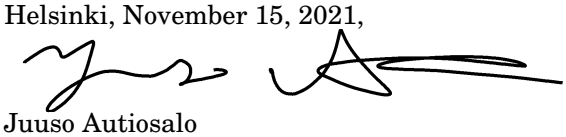
final project seminar, giving me the confidence that developing the Digital Twin Web approach would be worth the effort. I also thank all other people involved in the DigiTwin project from Konecranes, Remion, RD Velho (now Huld), IDEAL PLM (now IDEAL GRP, part of Atos), and Siemens Osakeyhtiö. And the people who visited the DigiTwin Demo Days or otherwise acted in the loosely defined DigiTwin network. The latter part of my dissertation work was done under the MACHINAIDE project, and I thank my colleagues, especially Pauli Salminen, for providing me the space to finish the dissertation.

Martti Mäntylä, Petri Kuosmanen, and Jari Juhanko were founding figures for the Aalto Industrial Internet Campus (AIIC) community. All of them have done a lot of behind-the-scenes work to keep wheels turning. Jari Juhanko also originally hired me to AIIC and trusted me with the freedom to develop Industrial Internet my own way. Heikki Sjöman welcomed me into a practical research project, giving me a flying start in prototyping Industrial Internet solutions. Petri Asikainen and Matti Kemppainen from Konecranes faithfully allocated their time to bringing industrial relevance to the research conducted at AIIC. Overall, the people of the AIIC community provided me with a fruitful mix of multidisciplinary idea exchange. Riku Ala-Laurinaho was a loyal research companion, playing a key role in discovering the Digital Twin Web. The colleagues at the Mechatronics (formerly Engineering Design) research group provided healthy social relationships and *mouho* to the daily research work.

Friends kept me along in life beyond research. My mentor Janne Huhtakallio taught me personal development and lit up a sleeping desire for business. Anna Jokinen patiently listened to my crazy ideas. My family provided me with a steady platform from which to jump to the academic world and where to come back when needed. I also want to thank every other soul I have interacted with, as your actions may have butterfly affected me to the success I have been blessed with.

Lastly, I thank the neural language processing research communities for the foundational knowledge behind the commercial writing aid tool I used for this dissertation. And Linus Torvalds for creating and maintaining Linux.

Helsinki, November 15, 2021,



Juuso Autiosalo

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Autiosalo, Juuso; Vepsäläinen, Jari; Viitala, Raine; Tammi, Kari. A Feature-Based Framework for Structuring Industrial Digital Twins. *IEEE Access*, 8, 1193-1208, January 2020.

II Autiosalo, Juuso; Ala-Laurinaho, Riku; Mattila, Joel; Valtonen, Mika; Peltoranta, Valtteri and Tammi, Kari. Towards Integrated Digital Twins for Industrial Products: Case Study on an Overhead Crane. *Applied Sciences*, 2021, 11(2), 683, January 2021.

III Ala-Laurinaho, Riku; Autiosalo, Juuso; Nikander, Anna; Mattila, Joel and Tammi, Kari. Data Link for the Creation of Digital Twins. *IEEE Access*, 8, 228675-228684, December 2020.

IV Autiosalo, Juuso; Siegel, Joshua and Tammi, Kari. Twinbase: Open-source server software for the Digital Twin Web. *IEEE Access*, 9, 140779-140798, October 2021.

Author's Contribution

Publication I: "A Feature-Based Framework for Structuring Industrial Digital Twins"

The author conceptualized the feature model with the help of Kari Tammi. The author formulated the overall framework with features and building blocks and defined the basic procedure for creating a digital twin instance. The author designed the feature-based digital twin analysis method. The author, Jari Vepsäläinen, Raine Viitala, and Kari Tammi performed evaluations for the implementation of the feature-based digital twin analysis. Jari Vepsäläinen conducted a correlation analysis of the features. The author formulated the one-sentence definition of digital twin with Jari Vepsäläinen and Tuomas Tiainen. The author wrote the manuscript, which was reviewed by Jari Vepsäläinen, Raine Viitala, and Kari Tammi.

Publication II: "Towards Integrated Digital Twins for Industrial Products: Case Study on an Overhead Crane"

Kari Tammi and the author planned and prepared the funding application for the project that was the main subject of the study with the help of several other university and industry representatives. The author acted as an academic project manager of the project jointly with Valtteri Peltoranta as an industrial project manager. Kari Tammi was the principal investigator of the project. The author participated in the development of all of the components of the digital twin as a project manager, developer, or advisor. Joel Mattila programmed and provided visualizations for the bearing lifetime estimation case described in section 3.7. The author conceptualized the study from a project work into an academic case study with Kari Tammi, Riku Ala-Laurinaho, and Joel Mattila. The author performed the analysis of the project, formulating the lessons learned for future digital twin

development. The author conceptualized the API-based business network framework presented in the study.

The author wrote the original manuscript with the following exceptions: Kari Tammi wrote a significant part of the introduction and Riku Ala-Laurinaho wrote parts of the methods (sections 2.3, 2.4) and results (sections 3.2, 3.3, 3.8, and 3.11). The manuscript was reviewed by the author, Riku Ala-Laurinaho, Miika Valtonen, Valtteri Peltoranta, and Kari Tammi.

Publication III: "Data Link for the Creation of Digital Twins"

The author was the second author of the study, mainly designed and implemented by Riku Ala-Laurinaho. However, the author was responsible for two targeted contributions that are essential for this dissertation. The author conceptualized and wrote the first draft of the digital twin document, which was developed to its published form by Riku Ala-Laurinaho and Anna Nikander. The author conceptualized and wrote Section "III. Digital Twin Web (DTW)" of the original manuscript.

Publication IV: "Twinbase: Open-source server software for the Digital Twin Web"

The author designed and implemented the study with support from Josh Siegel and Kari Tammi. The author conceptualized and designed the structure of the Digital Twin Web, the "GADIT" architecture, and the digital twin identifier registry. The author designed and wrote the "Twinbase" software presented in the study and planned and conducted the measurements. The author wrote the original manuscript, which was reviewed by Josh Siegel and Kari Tammi.

Language check

The language of my dissertation has been checked by Grammarly. I have personally examined and accepted/rejected the results of the language check one by one. This has not affected the scientific content of my dissertation.

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Abbreviations

API Application programming interface

AAS Asset Administration Shell

CI Continuous integration

DNS Domain Name System

DT Digital twin

DTDL Digital Twins Definition Language

DTID Digital twin identifier

DTW Digital Twin Web

FDTF Feature-based digital twin framework

GADIT Git-based architecture for digital twins

HTML HyperText Markup Language

ID Identifier/identity

IoT Internet of Things

NASA National Aeronautics and Space Administration

NGSI-LD Next Generation Service Interfaces - Linked Data

OPC UA Open Platform Communications Unified Architecture

PAR Participatory action research

PLM Product lifecycle management

REST Representational state transfer

URL Uniform Resource Locator

WoT TD Web of Things Thing Description

WWW World Wide Web

YAML YAML Ain't Markup Language

1. Introduction

Digital twins are virtual entities that are linked to real-world counterparts. They can be made of a wide range of features, such as data, simulation, and artificial intelligence. The features are selected to best serve the needs of the problem that the twin has been made to solve. The most prominent use case has been to mirror and simulate the behavior of various physical objects. The term digital twin was first used in the current technical meaning by the aerospace industry in the early 2010s [121, 139], from where the term first spanned to manufacturing [107, 19, 52, 89, 135] and then to other disciplines such as built environment [87, 109, 64] and healthcare [22, 77, 16]. The term, however, has many synonyms, and virtual counterparts have been made for things even longer [21, 73, 35], and conceptual mirror worlds were suggested much earlier [37]. Some even see a conceptual resemblance to the *theory of Ideas* introduced by Plato [108].

Regardless of what digital twins are made for, their core premise is that "information is a replacement for wasted physical resources" [47]. Twins save resources by bringing the right information to the right place at the right time, leveraging their positioning as bridges between the physical and digital worlds. Digital twins also seem to be the missing architectural piece that will make the Internet of Things (IoT) actually work. When an IoT device goes to sleep to save its physical resources, its digital twin is still awake, responding to queries from external parties and waking up the device if needed. Digital twins can also give intelligence to objects that have no computation capacity but can be identified somehow. In the future, digital twins might even be required for building cyber-physical products, similarly as embedded software is needed for building mechatronic machines.

This dissertation project was initiated to boost the adoption of Industrial Internet technologies. Digital twin was selected as a topic even though at the time it was primarily just an exciting concept and nobody knew what exactly to do with it. Digital twin was seen as a concept that would fix almost any problem. Now we know that this initial assumption was mainly

right because the digital twin concept can ingest pretty much any digital technology. But it also became painfully clear that making even one digital twin can be an overwhelming task.

Research work started with long-lasting conceptual exploration coupled with hands-on digital twin development, leading to the revelation of the technical pain points and essential methodologies in the development of digital twins. The methodologies were numerous, ranging from user-friendliness to standardization. One technical pain point was taken under further development: creating scalable twins could be more approachable if each twin had a "data link" that connects both to internal components and to external twins and applications. We performed quick experimentation of the data link idea, giving the confidence to continue with a "digital twin document" approach. The last article then presented a platform for the data-linking digital twin documents. The latter part of the work also included developing a general approach for building a human and machine-readable network of digital twins, materializing in the "Digital Twin Web" initiative.

1.1 Research problem

The initial goal of this work was to develop a digital twin that could be used to enhance machine design methods. Hence, this work set out to define digital twins, build proof-of-concept digital twins, and enhance machine design practices with digital twins. As additional goals, the work was supposed to look for value-adding use cases for digital twins and find out if it would be feasible for every product to have a digital twin. The digital twins were also supposed to combine information from multiple sources. A preliminary assumption was that the basic digital twin technologies were already available and could be leveraged during the work.

However, during the definition and proof-of-concept building, it turned out that the existing digital twin tool offerings were too underdeveloped to enable explorative development of methodological improvements to machine design methods. The initial goal of improving machine design methods could therefore not be effectively implemented, and the latter phase of the work concentrated on developing digital twins as a general tool that could be used for machine design in later works. Hence, the overall research problem of this study was:

Research problem: How to build digital twins for industrial products?

The problem had an industrial viewpoint, although, during the study, it turned out that because the core of digital twins consists of interlinked metadata, digital twins of industrial products will need to be compatible

with non-industrial digital twins to be effective in their purpose. Hence, while the motivating research problem stayed in the industrial domain, the work concentrated on finding the common methodologies for building any kind of digital twins.

1.2 Research goal and questions

The most concrete research goal was to build a digital twin for an industrial overhead crane. This digital twin should be useful for maintaining the existing cranes and designing better new cranes. After the first stage of the research, the extensive amount of work put into developing only one twin was seen as a limiting factor for the industrial adoption of digital twins. Hence, the research goal shifted towards finding methodologies for creating scalable networks of digital twins.

At the start of the research, digital twins were not unanimously defined, so before the work towards building a digital twin of a crane could be properly started, we had to come up with a definition for digital twins. This need led to the formation of Research Question 1:

RQ1: What is a digital twin?

This research question was the main topic of discussion for Publication I, although it still remains a global conversation piece. Nevertheless, the publication answered the question enough for our purposes. The first question was intended as a preparatory question for Research Question 2:

RQ2: How to build a digital twin?

In practice, we worked on RQ1 and RQ2 simultaneously as the solutions of Publication II were being built before Publication I was finished. Publication II built a concrete digital twin for an industrial crane in a collaborative effort between the university and industry representatives. The work on developing a concrete twin revealed difficulties in creating scalable digital twins, leading to Research Question 3:

RQ3: How to build a network of digital twins?

The experiments of Publication III initiated and confirmed a new concrete research direction on how to implement scalable digital twins. This direction was continued in Publication IV, which provided a more thorough answer to RQ3.

The research questions were investigated with three main research meth-

ods, Grounded Theory, participatory action research, and design science presented in section 3.1. All of the research work for this dissertation leveraged the Ilmatar overhead crane located at Aalto University premises as a reference environment, although the use was most prevalent in Publication II and Publication III.

1.3 Scientific contributions

This dissertation presents four main contributions shown in Figure 1.1. Publication I presents a definition for digital twins along with a frame-

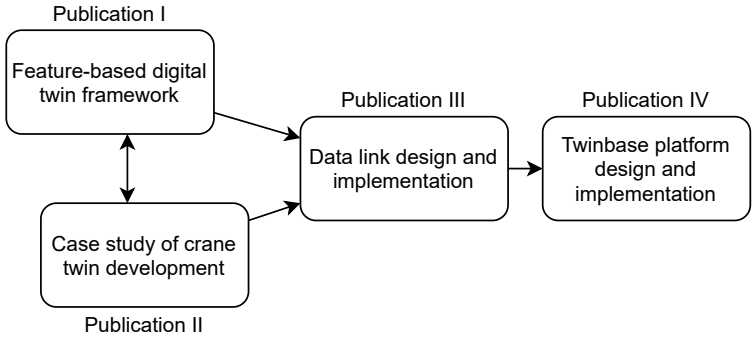


Figure 1.1. Primary contributions of the thesis.

work that supports the development of technical implementations that follow the definition. Publication II shows a practical example of what a multi-component digital twin of a crane can look like when built with currently available tools and identifies problems and good practices for developing more scalable twins. Publication III explores preliminary methods for building networked digital twins, and Publication IV introduces an architecture and software solution for building a global network of digital twins. The two latter publications also describe the "Digital Twin Web" initiative, a suggested direction for future research.

From the perspective of mechanical engineering, this dissertation work developed the digital twin concept from an ambiguous concept towards a tool that can be leveraged when designing future machines. With the platform presented in Publication IV, mechanical engineers can start experimenting with different ways to leverage publicly available digital twin description documents. Hence, the main contribution of this dissertation work was to take the general digital twin concept and turn it into a general tool for building digital twins.

2. Literature review

General interest in the digital twin term is starting to be noticeable. A Google Trends comparison in Figure 2.1 shows that while interest in the search term “internet of things” peaked in 2016 and has been lowering since, interest in "digital twin" has been rising steadily from nearly unnoticeable interest in 2016 to its current peak with half as much interest as the Internet of Things term [44]. Google Trends represents a largely unfiltered sample of search requests made to Google, and while the data is not scientific and merely reflects search activity instead of actual popularity [43], the slow but steady rise of interest in digital twins seems indisputable. In support of this trend, digital twins have started featuring in increasingly mainstream news publications, such as Forbes [83], Financial Times [136], and Washington Post [45].

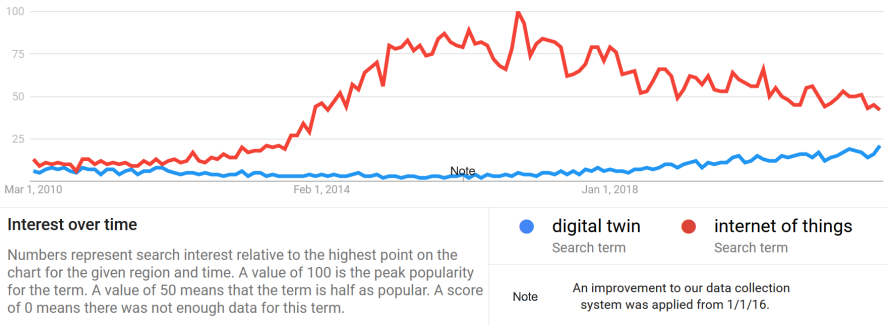


Figure 2.1. Google Trends comparison between “digital twin” and “internet of things”. Modified from [44].

In the academic world, the digital twin term has attracted many publications: the exact search parameter “digital twin” receives 24 000 hits on Google Scholar, 3 966 on Scopus (within title, abstract, and keywords), and 1 784 on Web of Science (within topic). These articles include dozens of reviews on the digital twin concept from various viewpoints. Nevertheless, the obscurity around the term remains, and the research work on digital twins has even been criticized as not reproducible [76].

Due to the sheer number of publications, a systematic literature review on the general digital twin concept proved to be infeasible for the purpose of this thesis. Even the amount of reviews is too large to be listed in this work, but I provide some useful and highly cited reviews on digital twins. Liu *et al.* review the concepts, technologies, and industrial applications of digital twins, concluding with a distinction that some researchers adopt a modeling-oriented view and some focus on information management-oriented digital twins [76]. Lu *et al.* identified seven research issues for digital twins in smart manufacturing [79]. Rasheed *et al.* reviewed the digital twin concept from a modeling perspective, citing 550 other publications [102]. Tao *et al.* provide a highly cited review on the state of the art of digital twins in the industry [131]. Qi *et al.* provide a thorough survey on the tools and technologies for digital twins [101]. Kritzinger *et al.* provided an early review that has received a high number of citations [69]. Also, an early review on digital twins for manufacturing by Negri *et al.* has received a high number of citations [89].

While the mentioned reviews provide an overall view of the state of the digital twin concept, I provide a historical outlook into the origins and recent history in section 2.1. Furthermore, as the latter part of the work concentrated on developing methods to create multiple digital twins, I conducted a systematic literature review on the *network of digital twins* topic in section 2.2.

2.1 History of the digital twin concept

According to the most established academic and industrial consensus, the digital twin *concept* was introduced by Dr. Michael Grieves in his presentation in 2002 [47], as shown in Figure 1.1. It was then called “Conceptual

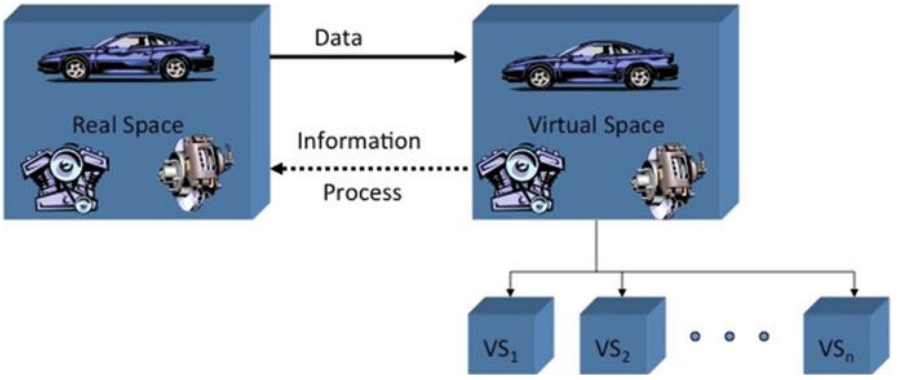


Figure 2.2. Conceptual ideal for PLM by Dr. Michael Grieves in 2002 [47].

ideal for PLM” (PLM = product lifecycle management), whereas the digital twin term was taken for wider adoption after it appeared in NASA’s strate-

gic roadmap draft in 2010 [121]. (Some articles state that the digital twin *term* was introduced in 2002 or 2003 by Dr. Grieves, but this is false.)

The original concept from 2002 contained a real space, virtual space, the data flow from real to virtual, information flow from virtual to real, and different instantiations of the virtual space. This basic model is still very much valid today.

The history of the concept is, however, much more nuanced. The following subsections describe the origins of the digital twin concept and how it has developed over the years. I focus on the term "digital twin" but also include other synonyms and phenomena that coincide with the digital twin concept, at least partially, especially when documenting the early origins of the concept. I concentrate on archived material, primarily academic publications, as a proper historical review on the state of digital twins outside those would require a significantly more thorough research approach, preferably including interviews with practitioners at the time.

2.1.1 Pre-2000

Several academic articles have created a connection between digital twins and Plato's "Allegory of the Cave" [61, 68, 85]. Some of my acquaintances have also sighted a resemblance to Plato's "world of Ideas". While these connections are distant and may not lead to any tangible implications, they suggest that the basic concept of mirroring the real world, which is essential to the digital twin concept, has existed since the times of Ancient Greece. It seems that the basic urge to create digital twins is a very humane phenomenon.

The concept of mirroring has also had technical implications. For example, it has been reported that NASA's Apollo space program (1961-1972) used physical twins of space vehicles for flight preparations, such as training, and for mirroring the condition of the vehicles and simulating alternative scenarios during flight, assisting the astronauts in critical situations [107, 19].

Coming to the digital age, the original World Wide Web (WWW) proposal by Sir Tim Berners-Lee in 1989 presented that each information node of the proposed system ideally "represents or describes one particular person or object" with examples including also concepts, types of hardware, and specific hardware objects [15]. Although as we know, the WWW has not yet been able to mirror exact real things very precisely, but rather separate nuggets of information on disorganized web pages. The first detailed conceptualizations of mirroring the real world with software seem to have appeared in David Gelernter's "Mirror Worlds" book in 1991 [37], as pointed out by more recent digital twin research [88, 23].

Towards the last few years of the second millennium, solutions for the closely related paradigm "Internet of Things" had started forming ways to

bridge the gap between real and virtual worlds [59, 13, 147]. Bruns also used the term "twin-object" for the virtual counterparts of his "integrated real and virtual prototyping" solution in 1998 [21]. Nevertheless, the digital twin concept had not been properly formalized by the turn of the millennium.

2.1.2 2000-2009

The start of a new millennium marked the commodification of Internet of Things research, which meant that an increasing amount of individual real-world objects started to have a digital presence. Several computer science-focused researchers started using the virtual counterpart term, starting with Langheinrich *et al.* in 2000 [73] and continued, e.g., by Främling *et al.* [35]. There were several synonyms for the phenomenon [8], including but not limited to product agent [35], product avatar [55], holon [86], and virtual proxy [73].

At the same time, product lifecycle management (PLM) was being developed as a methodology for managing the engineering information related to a product. Dr. Michael Grieves introduced the "Conceptual ideal for PLM" in his 2002 presentation in a University of Michigan presentation to industry [47], and the concept was included in a journal article in 2005 [48] and in a seminal book on PLM in 2006 [46].

In 2005, the "digital twin" term was mentioned in images of one conference paper [90] but did not yet reach wider adoption. Overall, the decade showed academic development of the digital twin concept on multiple fronts of computer science, control engineering, and mechanical engineering.

2.1.3 2010-2014

In June 2010, Puig and Duran presented a conference paper, "Digital twins" [100], that focused on creating recognizable avatars of humans instead of the technical mirroring approach. This can be viewed as a demonstration that the term "digital twin" can have a meaning also outside the engineering circles.

In November 2010, NASA published a draft of its strategic roadmap, defining "digital twin" as an approach for simulation-based systems engineering [121]. The first sentence of their definition was: "A digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin." [121]. The described digital twin is a high-fidelity physical model that is updated with sensor data of the real counterpart from several sources.

The newly defined digital twin paradigm created a buzz among aerospace researchers, including a thorough general description of digital twin as-

pirations for NASA and the United States Air Force [40] and more targeted investigations on modeling and predicting the structural life of airframes [139, 138, 42]. Towards the end of the first half of the decade, there was a study on modeling as-manufactured geometry with a focus on cracking mechanisms [25].

Research under other terms progressed as well, featuring, for example, a study on using social media as a platform for product avatars [153]. Still, the first half of the 2010s can be seen primarily as the inception of the digital twin term by aerospace researchers.

2.1.4 2015-2019

The second half of the 2010s presented a massive growth of the usage of the digital twin term in academic publications. In 2015, Ríos *et al.* reviewed the overall concept and compared the twin and avatar terms, although still focusing on the implications on aircraft [110]. Rosen *et al.* described how to use digital twins in manufacturing [107].

2016 broke the academic use of the digital twin term free from the aerospace industry with several publications focusing on general manufacturing and simulation. Boschert and Rosen described the digital twin concept as the next wave in simulation technology, featuring *assistance along the entire life cycle through linkage to operational data* as an upgrade from simulation-based system design [19]. Schröder *et al.* spanned the concept outside of the simulation focus, exploring the visualization of digital twins with web services and augmented reality [117]. Canedo described digital twins as a solution to manage (industrial) IoT devices throughout their lifecycle via a graph-focused approach where real-world objects are represented by a subgraph of nodes [24]. Holler *et al.* performed a thorough literature analysis for digital twin concepts in manufacturing, covering several related terms [52]. (For some reason, perhaps due to bad indexing and difficult availability, this publication has not been cited much despite its high quality and comprehensiveness.) Research under other terms often developed some specific aspects of digital twins; for example, *data proxies* were used to estimate the state of objects with minimal input data [125, 124].

From 2017 onward, publications on digital twins are too numerous to be all described here, but I give some highlights. Negri *et al.* wrote a review on the digital twin concept from a manufacturing perspective [89]. West and Blackburn assessed the affordability of digital thread and digital twin concepts, comparing them to the Manhattan Project and concluding that it is impractical to implement them to the full extent [148]. Schleich *et al.* developed a digital twin reference model focusing on geometrical variations management [115]. Grieves and Vickers published a book section explaining the origins and implications of the digital twin concept [47]. Tao *et al.*

wrote several influential papers on digital twins, featuring the introduction of the "Digital Twin Shop-Floor" paradigm [135], a general paper on design, manufacturing, and service [131] (which is the most highly cited "digital twin" paper according to Scopus), and a review on state of the art in the industry [134].

The last years of the decade also included publications outside the manufacturing domain [87, 22], but the general situation at the turn of the decade is well summarized by the Nature commentary "Make more digital twins" by Tao and Qi, which focused heavily on manufacturing but also mentioned other application areas such as forest management [132].

2.2 Systematic review: network of digital twins

The "Digital Twin Web" phrase in the title of this dissertation refers to a certain type of network of digital twins defined in sections 4.3.2 and 4.4.2 and discussed in section 5.4. The initial formalization of the Digital Twin Web is seen as a significant result of this work, rendering a targeted literature review on the network of digital twins appropriate.

Earlier literature on networks of digital twins is scarce, so a systematic literature review is possible. To keep the number of results manageable, the search included four exact search strings in Scopus and Google Scholar databases. The search strings and the resulting references are shown in Table 2.1. The table also includes references that have caught my attention at some point but did not appear in the search.

A total of 57 relevant publications were found, although five of them [140, 103, 119, 130, 145] were partly inaccessible. Nearly all of the publications gave the impression that some kind of network of digital twins is destined to exist in the future, but properly generic methodologies for building a network of digital twins were not found. Hence, research on the generic implementation of digital twin networks is well motivated.

Focus levels on the "network of digital twins" topic varied. 17 publications focused strongly on developing some kind of digital twin network [24, 4, 67, 127, 128, 154, 6, 29, 53, 74, 78, 105, 119, 118, 130, 152, 158]. 31 publications gave moderate focus, for example, not describing the network aspects deeply enough, or developing a digital twin for some specific purpose, and mentioning the networking aspect as potential future research [30, 116, 54, 58, 80, 113, 112, 144, 31, 70, 71, 81, 106, 3, 11, 17, 32, 62, 75, 79, 111, 2, 10, 49, 56, 84, 104, 120, 155, 156, 157]. 7 publications showed low focus, essentially just mentioning the concept while concentrating primarily on some other topic [7, 140, 18, 91, 26, 82, 146]. The focus level of 2 publications could not be categorized due to inaccessibility [103, 145].

Two general types of "digital twin networks" emerged from the literature.

Table 2.1. Results of literature search for networks of digital twins. The search was conducted on 5-6 September 2021.

Search term	Database	Results	Relevant	Total		References	Total
"digital twin web"	Scopus	0	0	2	2020	[4]	57
	Google Scholar	9	2		2021	[49]	
"web of digital twins"	Scopus	0	0	2	2020	[3]	
	Google Scholar	2	2		2021	[105]	
"network of digital twins"	Scopus	2	2	33	2018	[7, 80, 140, 144]	
					2019	[18, 31, 71, 81, 91, 103, 106]	
	Google Scholar	37	33		2020	[4, 11, 17, 26, 32, 62, 67, 79, 82, 111, 127, 128]	
					2021	[6, 10, 49, 74, 84, 104, 119, 118, 145]	
"digital twin network"	Scopus	7	5	16	2020	[75, 154]	
	Google Scholar	60	13*		2021	[29, 53, 56, 78, 84, 118, 120, 130, 146, 152] [155, 156, 157, 158]	
Additional**				8	2016	[24]	
					2017	[30, 116]	
					2018	[54, 58, 113, 112]	
					2019	[70]	

* Relevance judged by the Google Scholar preview.

** Identified during earlier research or from references. Includes also blog posts and marketing materials.

A digital twin network can refer to a network of software components for one digital twin or to a network of multiple twins. Most publications did not distinguish which type of network was under consideration, and in fact, in some cases, the division between these two types was indistinguishable as the presented architecture made these two types intertwine with each other. One twin was not a clearly defined entity, but the whole network of twins was implemented in one technical solution where resources were shared by all of the twins. In other cases, the whole network of twins was referred to as one twin.

As a special terminological case, some publications used the "digital twin network" term to refer to a digital twin of a telecommunications network consisting of several sub-twins. These publications often presented a technical implementation with simulation or measurement results. This is a perfectly valid network of digital twins, but its special purpose makes the presented architectures not directly applicable for creating generic networks of digital twins.

Application areas included manufacturing, telecommunications, infrastructure, vehicles, medical, business ecosystem/supply chain, and personal digital twins. Artificial intelligence or machine learning was in the focus of several publications, often showing methods for training the neural networks of digital twins. The social networking expression was used to refer both to mirroring the social relations of people and to describing machine-to-machine communications.

2.3 Research gaps

The following four research gaps identified from the existing literature were especially relevant for this dissertation work:

Methodologies for implementing a network of digital twins. Almost all of the publications found in the systematic review assumed that there would be a network of digital twins in the future. Also, Kaivo-Oja *et al.* [66] identified a move towards larger interconnected networks as one of three major shifts for future digital twins. I formalize these assumptions and observations into the research gap of developing methodologies for implementing a network of digital twins.

Platform for web-based digital twins. This gap has appeared in some publications [122, 142] and is well summarized by Ricci *et al.*: "... exploiting the web as basic platforms for enabling interoperability at the application level for Internet of Things systems. ... A clear direction suggested in this case is to conceive and design digital twin platforms for executing and managing digital twins as hypermedia-based decentralized middleware based on the web and its technological stack." [105]

Standards for digital twins. Standards for digital twins have been

discussed in several publications, especially by industry practitioners [60, 50, 12]. An ISO (International Organization for Standardization) standard for digital twins in manufacturing is under development [1], and research should support that standardization process. The research gap is well summarized by Lu *et al.*: "Research issue 4: standards for Digital Twin. Though anyone can develop a Digital Twin solution using common technologies, standards will facilitate the longevity of a Digital Twin solution. Standard-compatible Digital Twin solutions can inherit the flexibility, interoperability and scalability of existing and new standards for information model and communication protocols. This is especially important when a Digital Twin will be deployed in an open network of Digital Twins." [79]

Cross-sectoral network of digital twins. This research gap is not mentioned by many researchers, but it is instinctively required for larger twin networks, such as for supply chains. The gap was also directly mentioned as future research by Al-Sehravy *et al.*: "Future research will include ... level of integration across organizations and sectors (local and independent DT or cross-sectoral web of DTs) ..." [3]

In addition to these four highlighted gaps, the academic body of knowledge in digital twins is, in spite of the high publication count, full of further research gaps. Valuable research can be conducted on several different fronts, such as creating more accurate simulations, enhancing interoperability, or developing more efficient processes for creating twins. In fact, the extent of the research gaps is so large that it does not seem appropriate to list all of them here. In addition to the future work described in this dissertation and its publications, readers can see lists of identified gaps in publications by, e.g., Lu *et al.* [79] and Tao and Qi [132]. Overall, I believe we still have decades of both research and practical work to do before digital twins fulfill the high expectations they have been assigned.

3. Methods and materials

3.1 Research methods

The research leverages three main research methods: Grounded Theory, participatory action research, and design science. The methods and their use is presented in subsections 3.1.1-3.1.3. The research relied on qualitative methods with the exception of a quantitative evaluation in Publication IV. The qualitative approach was selected due to the nature of the research, i.e., figuring out what the whole digital twin concept was all about and finding relevant future research and development topics rather than evaluating and improving an existing solution.

A traditional mechanical engineering method, experimental research, is not included because the digital twin concept was unclear at the beginning of the research work. Diving into experimental research would have skipped finding out what a digital twin actually is, and therefore the experimental results would not necessarily have been about digital twins at all. In the last publication, measurements were conducted to evaluate the design, and it is possible that experimental research on digital twins can be implemented after this work.

3.1.1 Grounded Theory

Grounded Theory is an inductive research method that is used to create initial theories from unstructured data through categorization. Grounded Theory was proposed by Glaser and Strauss in 1967 [41] and conveniently summarized with recent trends by Saunders [114]. Grounded Theory has traditionally been used by various branches of social sciences, although recently also software engineering has adopted the method [129].

The purpose of Grounded Theory is to provide a methodologically guided path from a set of unstructured data into a potentially novel theory that is grounded in that data. The research should ideally be started with no

knowledge of existing theories in the area to avoid bias towards those theories. Instead, the researcher should start recognizing patterns in the data with no presumptions, therefore leading to a theory that is instantiated solely by the data the researcher has acquired during the study.

In this dissertation, Grounded Theory was used as the primary guiding method in Publication I and supportive method in Publication II. However, either of the publications did not follow any strict coding practices but rather just leveraged the basic idea of generating theories from data. The use of the method is further described in Publication I.

3.1.2 Participatory action research

In participatory action research (PAR), researchers participate an ongoing activity in an effort to gather data about the activity [27]. The researcher has a double role in performing actions, typically as a manager, and researching those actions. PAR is a research method that allows rich data collection but demands strong personal skills and brings in the risk of researcher bias [126]. PAR has been seen as especially suitable for irreversible processes such as product development [93].

This dissertation used PAR as a method for conducting the research of Publication II. The author acted as a project manager and researcher of a digital twin development project similarly as described by [93]. The risk of researcher bias was alleviated by leveraging material written during the project in the analysis phase and including negative observations in the final results. The author had also conducted PAR research earlier as a team member of a shorter development project in the same environment [126].

3.1.3 Design science

Design science is a research method that includes designing a research artifact and evaluating it [51, 99, 33]. (The design phase implicitly includes building the artifact.) Before designing the artifact, a relevant problem needs to be identified, and its objectives defined [51, 99, 33]. Evaluation can be performed in twelve methods that can be categorized as observational, analytical, experimental, testing, or descriptive [51].

This dissertation leveraged design science as the main research method in Publication III and Publication IV. The main artifact (from the viewpoint of this dissertation) of Publication III, the “digital twin document” specification, was evaluated mainly in descriptive methods by forming *informed arguments* about the utility of the artifact and constructing *scenarios* around the artifact. Publication IV built and presented the “Twinbase” software and evaluated it through *informed arguments*, and performed a *dynamic analysis* that measured the response times of the system.

3.2 Materials

The materials used during the study included an industrial overhead crane called “Ilmatar” and a research project that developed a multi-component digital twin for the crane named “DigiTwin”.

3.2.1 Ilmatar the overhead crane

Ilmatar is the name of an industrial overhead crane installed at Aalto University premises in 2016 [8], shown in Figure 3.1. It was manufactured

Figure 3.1. Ilmatar the overhead crane. Reprinted from Publication II.

and donated to Aalto University by Konecranes. The purpose of the Ilmatar crane is to act as a collaboration platform for industrial internet and digital twin focused education, research, and innovation [8]. The platform was labeled as “Ilmatar OIE (Open Innovation Environment)” in 2019, with a list of openly accessible resources available at `https://aalto.fi/ilmatar`.

Ilmatar is a Konecranes CXT crane with a maximum lifting capacity of 3.2 tonnes. Its hook can move in the three dimensions of a cartesian coordinate system that correspond to bridge, trolley, and hoist with movement ranges of 19.8, 9.0, and 3.0 meters, respectively. (The hoist has a total rope height of 6.0 meters that can be used in limited areas of the laboratory space.) The hook of the crane rotates freely along a vertical axis.

The crane has several smart features, out of which the sway control enables other features, such as target positioning. The crane also has a customized OPC UA (Open Platform Communications Unified Architecture) interface that enables accessing a subset of crane control logic data and moving the crane with external software. Data from the crane are gathered to Konecranes systems via undisclosed proprietary solutions and to a university-administered MindSphere tenant via the OPC UA interface.

Ilmatar crane acted as a reference environment throughout the dissertation work, and Publication II leveraged it as the main subject of study. From the other publications, Publication III presented its technical solutions with Ilmatar as the primary use case, Publication IV used Ilmatar as a supportive example, and Publication I mentioned the digital twin of a crane as a target of future work.

3.2.2 Project for twin development

The Ilmatar crane was installed with the purpose of initiating practical research on the Industrial Internet topic. By the time the research for this dissertation started, the digital twin concept had been chosen as the main topic of an upcoming industry-university collaboration project called “DigiTwin” (`https://www.aalto.fi/en/aiic/digitwin`). This project was the primary raw data source for this dissertation.

The data of the project was gathered with the PAR method, consisting of observation through participation and the written material produced during the project. Descriptions of the developed twin components are available in Publication II. Furthermore, a master’s thesis implemented during the project [143] provided data about the project from the viewpoint of the dynamics of industry-university collaboration.

4. Results

The main results of the thesis consist of a conceptual framework, a case study, technical experimentation, and platform implementation, as presented in Figure 1.1. The framework development was the first topic of research, although it was soon joined by the case study on crane digital twin development. These two were implemented largely in parallel, feeding each other. The knowledge from the two studies was used for implementing techno-conceptual experimentation of a digital twin document, which was regarded worthy of a technical distribution platform. The results are gathered together in the "Digital twin Web" initiative described in Publication III and Publication IV.

4.1 Feature-based framework

The feature-based digital twin framework (FDTF) introduced in Publication I presents three main results:

1. Definition of digital twin
2. Identification of the feature-based nature of digital twins
3. Conceptual instructions on how to build modular digital twins

The feature-based digital twin framework states that digital twins consist of ten features presented in Figure 4.1. The features are leveraged based on the needs of the underlying use case of each digital twin and implemented by digital twin building blocks realized by various software components. It is important to acknowledge that the feature division exists only in the conceptual dimension, and actual digital twin building blocks consist of several features that are needed to implement the purpose of that building block. The features can be used to categorize and compare digital twin implementations with the feature-based digital twin analysis method, which is a part of the framework.

The following subsections present the definition (4.1.1), features (4.1.2), and building blocks (4.1.3) of digital twins, followed by the explanations of

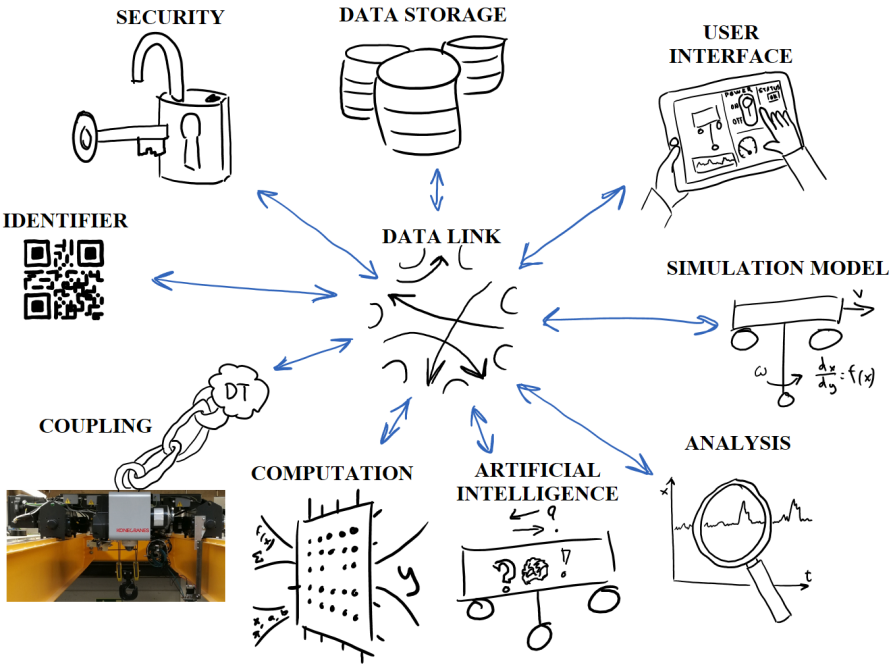


Figure 4.1. Features of digital twins. Reprinted from Publication I.

modular digital twins (4.1.4) and the feature-based digital twin analysis method (4.1.5).

4.1.1 Definition of digital twin

One of the main goals for the thesis work was to answer the question "What is a digital twin?" The framework presents a general definition in two sentences:

> "Digital twin is a virtual entity that is linked to a real-world entity. Digital twin consists of various features that are selected and customized to serve the needs of diverse use cases." (Publication I)

The first sentence describes the very basic essence of the digital twin concept in three parts. First, a twin is something virtual, which is used as a synonym for digital. Second, a twin *is* always *linked to* something. Third, a twin is defined by its relation to something in the real world, i.e., *a real-world entity*.

The second sentence opens up the contents of digital twins through the feature lenses, stating that digital twins can consist of pretty much anything with the purpose of serving its use case. This definition leaves even frustratingly much freedom to what actually is a digital twin, but the research work suggests that the digital twin concept is, in fact, very

flexible and almost like a blank canvas that can be filled with various digital technologies.

4.1.2 Features

The exploration of the essence of the digital twin concept led to the discovery of their feature-based nature. The feature-based nature means that all digital twins consist of a distinct set of features, no matter who built them and for what. A set of distinct digital twin features can also help categorize and compare digital twin implementations with analysis methods described in subsection 4.1.5

We attempted to identify the general features of digital twins from literature and discussions with practitioners and found ten features presented in Figure 4.1. Digital twins leverage the features based on the needs of the underlying use case, a fact which is leveraged by the "conceptual instructions on how to build modular digital twins" described in subsection 4.1.4. The features are implemented by building blocks described later in subsection 4.1.3

To evaluate the uniqueness of the features, we performed a correlation analysis on the appearance of the features in seven digital twin implementations described in academic publications. The analysis showed that the features appear mainly independently from each other, although artificial intelligence and analysis showed correlation. However, the sample amount was too small to make final deductions, and the analysis could now be duplicated with a larger amount of samples thanks to the appearance of more publications describing digital twin implementations.

Summarized descriptions of the ten identified features are:

Data link. The data link is a feature that ties other features together. It acts as the glue that ties the digital twin together, and the pure feature represents nothing else but the internal linking of other components.

Coupling. Coupling is the link between a digital twin and its real-world counterpart. Each digital twin must have at least one coupling to be called a digital twin due to the definition of the digital twin concept. Coupling can be implemented in several different ways. The acceptance of coupling methods is a heated topic of discussion, with some saying that the data flow through the coupling must be *automatic* in both ways [69], while my suggestion is that the data flow only needs to be *regular* in both ways, as some things can only support manual information transfer.

Identifier. An identifier is a piece of information that identifies a digital twin and, if possible, also its real-world counterpart. The real-world identifier then directs any real-world users to the corresponding digital twin. The exact requirements for digital twin identifiers are still mainly undiscovered, although further discussion is presented in Section 4.4.3.

Security. Security includes both the innate security of digital twin

components, provided by the “secure by design” principle [151], and the additional security-focused components, such as user management, cognitive firewalls [123], and proactive cyber defence [150].

Data storage. Data storages store the information contents of twins in a variety of digital mediums and formats. Mediums range from the internal memory units of processors to external hard drives, and formats include file-based, block-based, and object-based storage systems. The information in the storage needs to be accessible in a manner and latency defined by the use case for the data. Usage of information often includes storing it in multiple places, at least temporarily, and when this information duplication happens, it is important to indicate the master data source to ensure the correct direction of data flow and the timeliness of the data.

User interface. A user interface is a method for external agents to access the digital twin. It is primarily considered to consist of human-readable interfaces, such as web pages, but can also provide interfaces for machine users, which are often referred to as application programming interfaces (APIs). The boundary between human and machine interfaces is ambiguous because some people are able to use machine interfaces to access information.

Simulation model. A simulation model is an executable collection of algorithms that are used to replicate the behavior of the real-world counterpart digitally. Simulation models can be used to predict the behavior of the existing counterpart in future scenarios or to try out if an upgrade would make the real thing work better.

Analysis. Analysis refers to the detailed inspection of data and information to generate new insights but not implementing any actions based on the insights. Therefore, the analysis feature does not include making changes to the analysis algorithms but rather performing routine calculations whose results are meant to be inspected by external agents. For example, an analysis-focused software block can generate a daily report of the condition of the real-world counterpart.

Artificial intelligence. AI is the practice of learning from the past and using the experience to make proposals or decisions on how to act in the future. AI includes making permanent changes to how it will behave in the future. The difference between a digital twin that has intelligence is comparable to the difference between regular and autonomous cars. A regular car always needs a driver to fulfill its purpose, whereas an autonomous car can drive on its own. Hence, in more earthly terminology, the AI of a twin can be referred to as its logic as long as it includes adapting to new situations.

Computation. Computation refers to turning a mathematical formula and input variables into a result. Computation is a low-level feature that is required for implementing many of the other features.

4.1.3 Building blocks

Digital twin building blocks are the pieces of software that are used to implement the features of a digital twin. A basic requirement for a digital twin building block is an application programming interface (API) from which it is linked to other blocks. To be useful, the block must also be available whenever and wherever it is needed by the other blocks. As for recommendations, the twin block APIs should be available via the internet, and the twins should follow the microservices architecture.

Any kind of software can be used as digital twin building blocks as long as the basic requirements are fulfilled. However, it is important to be aware that not all software marketed as digital twin software fulfills these requirements, or the requirements may be only partially filled. Even if the software has an API, the API may not provide access to the desired features, rendering the software unusable for some use cases. Also, the availability is relative as a twin assembled at one developers' desktop environment may not be easily available for other developers. So it is important to know what kind of APIs are needed and where they need to be accessible when selecting software to be used as digital twin building blocks.

A simple way to counter the accessibility issue of the blocks is to make them available via the internet. Then security measures need to be put in place, but access to the block becomes more convenient. It is also common practice to keep internet resources constantly available, and also this makes twin blocks more usable.

The microservice paradigm can be used when there is a need for customized services for individual twins. Launching a microservice block for each twin is probably more efficient than launching a monolith, as one twin should use only little resources, and the microservice architecture allows the blocks to be scaled efficiently based on demand. Also, development cycles can be faster as only a small piece of software needs to be updated at a time. However, the microservice paradigm should not be followed blindly, and the size of the blocks should be decided based on holistic evaluation rather than trying to make it as small as possible. Using services provided by monolithic software can fit some situations well, but their limitations in comparison to microservices should be acknowledged.

4.1.4 Modular digital twins

The feature-based digital twin framework presents two basic concepts that enable modular digital twins: the data link feature and the building blocks of digital twins. A modular digital twin is a twin that has a data link that can be used to easily attach new blocks and detach unneeded ones. The modularity is comparable to modular physical products, such as a desktop

computer whose hard drive, graphics card, and other components can be added and swapped on demand.

In addition to the modularity enabled by changeable building blocks, modularity can also mean modifiable parameters of the twin. For example, the length of a crane can be modified so that several cranes can be created by modifying the same basic twin. This essentially introduces *digital twin classes*, which are preconfigured further than a general twin, but requires parameters to be selected before deployment.

The modular digital twin paradigm uses a star-shaped communication scheme in contrast to a grid style. In the computer metaphor, the data link in the center of the star corresponds to the motherboard of a computer which connects the other components together. Although, the data link may be used only to initiate the connections instead of actually relaying data between the blocks.

The implementation of the data link is not part of the framework, but it was investigated later in Publication III and Publication IV. Nevertheless, the framework suggests a build procedure for modular digital twins leveraging the features as a design aid. The process is defined in five-plus-one steps:

1. Define the functional requirements of the twin based on the underlying use case.
2. Determine the necessary features of the twin based on the functional requirements.
3. Select the building blocks that fulfill the corresponding features.
4. Configure the building blocks to the use case.
5. Deploy the building blocks to form an operational digital twin instance.

\+ Optionally create a digital twin class based on the instance.

The optional class creation step can be implemented at various phases, leading to digital twin classes defined in various levels of detail.

4.1.5 Feature-based digital twin analysis method

The feature-based digital twin analysis method can be used to compare digital twins based on a user-defined emphasis of features. The proposed analysis process includes a manual evaluation of the presence of each feature in the evaluated twin implementation. To get a general evaluation, users of the method can value all features equally, although we suggest that the data link feature is emphasized in the general evaluation.

The method gives a single score as the output of the evaluation, called *holistic score (Hs)*:

$$Hs = \frac{\sum_{i=1}^{n} w_i v_i}{\sum_{i=1}^{n} w_i v_{max}} Sc,$$

where n is the number of features, i is an individual feature, w_i is the weight factor, v_i is the value assigned to a twin in manual evaluation, v_{max} is the maximum value of evaluation, and Sc is the preferred scale that determines Hs to be in the range $0...Sc$.

The feature-based digital twin analysis method was leveraged to evaluate the presence of the features in seven digital twin implementations found in academic literature, but due to the low amount of data, the method remains unvalidated for the time being.

4.2 Case study on Ilmatar crane

Publication II describes a case study of developing a digital twin for an industrial overhead crane called Ilmatar in collaboration between the university and industrial partners. The main results of the case study include:

1. Example implementation of a multi-component digital twin of an industrial crane.
2. Identification of easy-to-use APIs as a major enabler of digital twin development, leading to the discovery of "API-based business network framework".
3. Several lessons learned from practical digital twin development.

4.2.1 Digital twin of Ilmatar the overhead crane

The multi-component digital twin of the Ilmatar crane was formed as a result of several years of research work by the university and company representatives. The work introduced eight new end-user applications supported by four intermediate building blocks, as shown in Figure 4.2. Descriptions of the components are omitted from this summary and can be viewed from Publication II. Some of the depicted applications consist of several building blocks and are simplified for visualization purposes.

The applications and building blocks were developed by several different groups as visualized by the colorings of Figure 4.2. During the development, we did not identify a system that could combine all of the applications, so the twin manifested itself in eight separate applications that had their own user interfaces. The separation makes it somewhat difficult to judge if something is a part of the digital twin or not, so we decided to include here only the applications that had a technical data connection to the crane. However, the user experience of the whole digital twin is very fragmented, and we decided to pursue an integrated digital twin in the future.

We defined integrated digital twin as "a collection of digital services available via a single digital location, linked to a single real-world entity." The link to a single real-world entity is clearly present in the Ilmatar

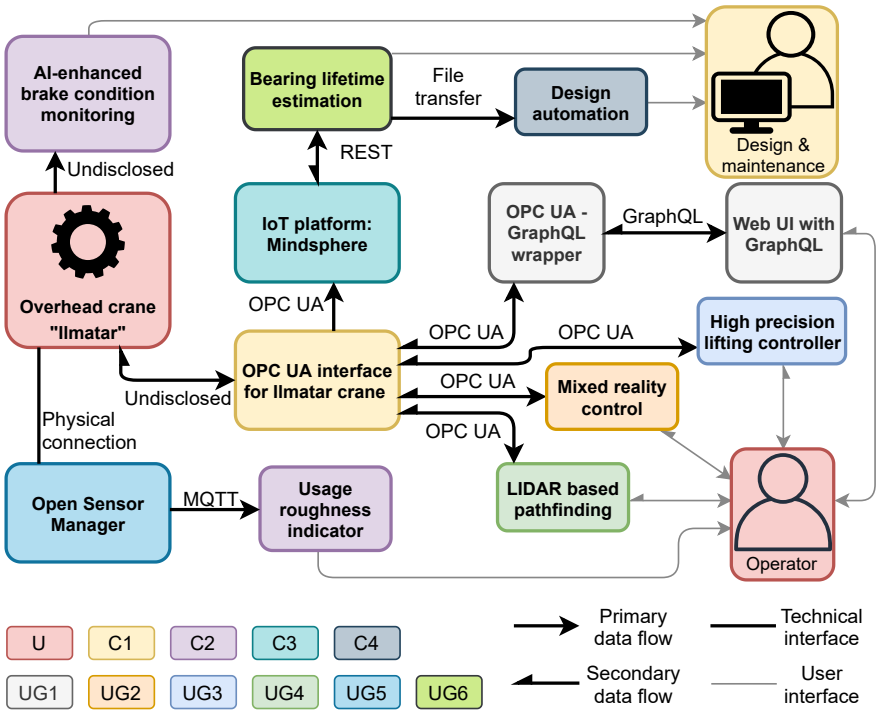


Figure 4.2. The structure of the multi-component digital twin of the Ilmatar crane. The boxes represent the crane itself, its digital twin building blocks, and the primary user groups. The arrows depict the technical and user interfaces between the blocks. The colors of the boxes represent the main development/-operating responsibilities of the university in general (U), companies (C1-4), or specific university groups (UG1-6). Reprinted from Publication II.

digital twin, but its components are definitely not available from a single digital location. The digital location can be human-readable, machine-readable, or preferably both. Potential examples include a human-readable web page, such as `https://aalto.fi/ilmatar`, a machine-readable collection of APIs, such as the API gateway presented in Publication III, and the human and machine-readable digital twin document used in Publication III and Publication IV. During the development work, APIs presented themselves as especially significant.

4.2.2 Easy-to-use APIs as digital twin enablers

Easy-to-use API can be defined as an API that can be used with only little effort by those who need access to the data behind it. During the development of the components of Ilmatar digital twin, easy-to-use APIs proved to be important enablers for efficient digital twin development. Technical APIs may also enhance the efficiency of human communication in digital twin application development and operation as suggested in the "API-based business network framework". However, ease-of-use is a difficult measure to leverage due to its inherent subjectivity.

Usage of APIs in Ilmatar twin development
The digital twin components of Ilmatar were connected to each other via APIs, as shown in Figure 4.2 and further described in Table 1 of Publication II. The methods of API usage can be organized into three main categories based on their positioning before the project: 1) Existing API server implementations were leveraged for new applications. 2) Existing software (i.e., software that was acquired before the start of the project) was used if it supported an appropriate API and could be used for application development. 3) New software that provided support for a needed API. The new software could be self-made or acquired during the development process.

Existing API server implementations proved to be significant assets for application planning and development because building a new operational API server was considered to be too large a task and mainly out of the scope of the project. The most prevalent existing API server used during development was the OPC UA interface of the Ilmatar crane. Five of eight cases leverage it directly, and one indirectly. In addition, the crane had a proprietary cloud connection that was leveraged by one case. Hence, existing API server implementations provided data for all but one application, forming a significant enabler for digital twin development.

Existing software was used during the project as much as possible as there already were licenses for them, and people were accustomed to using them. However, not all software has commandable APIs: they either lack them totally or learning them would take too much time for them to be

used in a project that has a limited time frame.

New software was taken into use when new features were needed, and user-friendly APIs were their most prevalent selection criteria. The development of the Ilmatar twin included both using appropriate software libraries or frameworks made by others and self-made software. For example, a general OPC UA library, "FreeOpcUa" (`https://github.com/FreeOpcUa/python-opcua`), was used, but also a new Ilmatar-specific software library was made for that (`https://github.com/AaltoIIC/ilmatar-python-lib`).

Use of new or existing software showed a division based on organization type: all company-developed building blocks used existing software, whereas the university-developed blocks were made primarily with software acquired during the project with only one exception (bearing lifetime estimation). Although, university developers preferred to use programming languages that they had used before the project.

API-based business network framework

The components of a multi-component digital twin may be developed and maintained by different organizations, as demonstrated by Figure 4.2. If this is the case, there needs to be both human and machine communication across organizational boundaries. Human communication includes a plethora of methods and purposes, such as speech, email, technical discussion, and business negotiations, whereas machine communication is more exactly defined and happens via APIs. The "API-based business network framework" builds on the observation that the communication structure between organizations of a multi-component digital twin is identical for human and machine communication and states that the organizational business network should be designed in parallel with the technical API network.

Using the API structure as a guideline for the design of organizational business relations should be straightforward because APIs are so exactly defined. The main reason to follow the framework is that the API structure of a multi-component digital twin can be seen as the digital supply chain of the digital twin end-user solutions, and it is only natural that business relations should follow that supply chain.

The framework emerged from the observation that the technical interfaces of Figure 4.2 represented both the human and machine communication channels between organizations during the digital twin development phase. However, as our twin components were made as prototype implementations for research purposes, the business aspect of the framework needs further validation from multi-organization twins used in actual production.

Subjectivity of ease-of-use
People experience the ease-of-use of systems, including APIs, differently depending on their previous experience with and knowledge of similar systems. For example, an experienced developer plunges right into a REST (Representational State Transfer) API with their preferred API discovery tools, whereas most people need guidance to a tool that can provide the data in a nice human-readable format. As the importance of APIs rises, the funders of digital twin development projects should consider the cost of missed opportunities when only a few people can access relevant data. However, estimating ease of use is not simple as it varies even by person, so the best advice we could offer was to acknowledge the problem strategically and tackle it when possible.

Further work could include performing System Usability Scale (SUS) or NASA Task Load Index (NASA-TLX) evaluations for the APIs, but both of these require extensive effort with several human test subjects to achieve reliable results and should be already available when assessing the potential APIs rather than being implemented for the purpose of comparing APIs for an individual project. In addition, the two methods provide usability scores for only one user group type per evaluation.

4.2.3 Lessons learned

The significance of easy-to-use APIs in digital twin development was the most prevalent lesson learned from the development work, deserving its own subsection. This subsection describes lessons learned in five additional topics: standards, tools, open source, skills, and goal setting.

Standards. There was a lack of standards for digital twins during the project. The lack was problematic as standards were seen as a requirement for building properly extendable digital twins. Especially metadata of the digital twin was seen as a potential topic for standardization.

Tools. The existing tools could be used efficiently for building singular applications, but creating integrated multi-component twins proved nearly impossible with current tool offerings. Also, launching digital twin services with 24/7 availability proved difficult without coding skills. Our best advice is to review your current toolset from these viewpoints and change if better tools appear.

Open source. Open-source software makes development faster thanks to being instantly accessible. All components built by “university groups” in Figure 4.2 leveraged open-source software. However, the project did not give insight into how open-source software would fare in production use.

Skills. Developing digital twins proved to require a wide range of skills from the developers. In addition to the domain skills in mechanical engineering, programming skills were highly useful, especially if there were no commercialized tools for creating the desired application.

Goal setting. Defining a clear, practical, and achievable goal led to good results during the project. Working on goals was seen as especially important because developing multi-component digital twins was uncharted territory, and no one really knew what the finished twin would look like. Goal definition also acted as a tool of cross-organizational leadership which can otherwise be challenging. The project had a practice of defining both far-fetching conceptual goals and short-term practical goals. This practice received both praise and critique from a clarity perspective.

4.3 Data link implementation

The results from the two earlier publications showed a need for a user-friendly method for assembling digital twin building blocks together. Publication III answers this need by introducing an implementation of the "data link" feature of FDTF. The introduced data link approach consists of a digital twin document and an API gateway. Also, the basic principles of the Digital twin Web were introduced. For the purpose of this thesis, the DT document and Digital Twin Web turned out more prevalent as such, whereas the API gateway acted primarily as a support for the data link approach. Hence, the main results of Publication III for this thesis are:

1. Introduction of the digital twin document.
2. Basic principles of Digital Twin Web.
3. Validation for the "Data link" approach of FDTF.

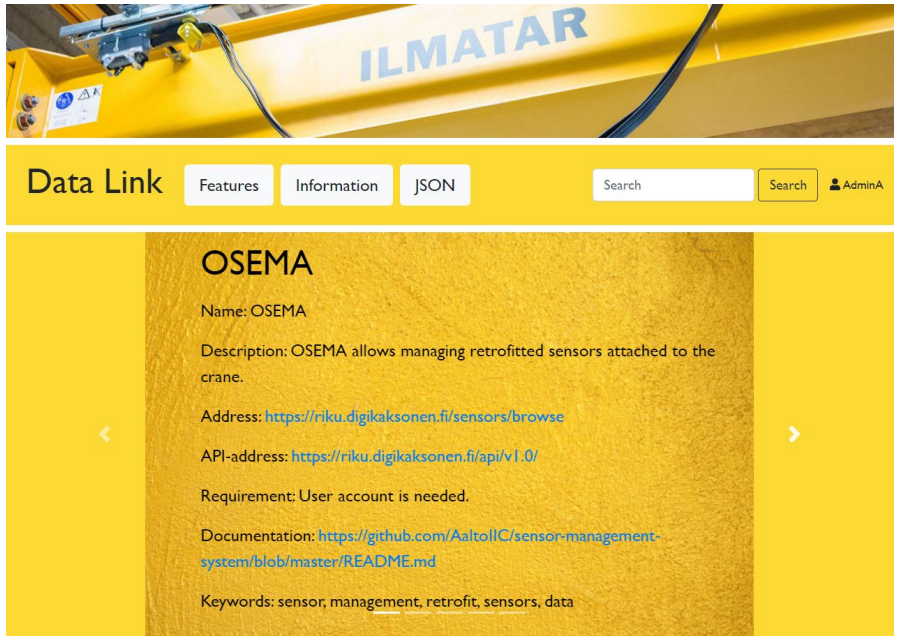
4.3.1 Digital twin document

A digital twin document is a human and machine-readable document that describes a digital twin the same way an HTML (HyperText Markup Language) document describes a web page. Digital twin documents can be extended with external twin blocks, similarly as HTML documents can be extended with external resources such as JavaScript files and video embeddings. The documents are also linked to each other semantically, i.e., providing both a hyperlink similar to a link on a web page and the type of relationship that the link represents between the twins. However, the digital twin document is still at a conceptual stage and requires further standardization to be efficient. We initiated a standard development effort focusing on user-friendliness.

Our initial DT document specification uses YAML (YAML Ain't Markup Language) for human readability, and we proposed some mandatory fields for the document, such as the standard version of the document, digital twin identifier, and display name for the twin. An example excerpt of a DT document for the Ilmatar crane is shown in Figure 4.3a. Even though YAML is fairly well human-readable, we also experimented with a more

```yaml
version: "1.0"
privacy: "public"
id: "http://d-t.fi/ilmatar-K16052"
name: "Ilmatar crane"
description: "The documentation of Ilmatar overhead crane"
createdMachine: "1605277810"
createdHuman: "2020-11-13T14:30:10.555Z"
modifiedMachine: "1605624649"
modifiedHuman: "2020-11-17T14:50:49.124Z"
owner: "Aalto-yliopistosäätiö"
contact:
  name: "John Doe"
  email: "john.doe@aalto.fi"
location:
  streetAddress: "Otaniemi"
  gpsCoordinates: "60.1841° N, 24.8301° E"
manufacturer: "Konecranes"
features:
  - name: "OSEMA"
    description: "OSEMA allows managing retrofitted sensors
      attached to the crane."
    address: "https://example.sensor.fi/sensors/browse"
    apiAddress: "https://digi.kaksonen.fi/api/v1.0/"
    requirement: "User account is needed."
    documentation: "https://github.com/AaltoIIC/
      OSEMA/blob/master/Documentation.md"
    keywords:
      - "sensor"
      - "management"
      - "retrofit"
      - "sensors"
      - "data"
  - name: "MindSphere"
```

(a) Excerpt of a DT document of Ilmatar crane in YAML format.



(b) The user interface of the data link showing the OSEMA feature described in the DT document of the Ilmatar crane.

Figure 4.3. Examples of digital twin document and user interface of the data link. Reprinted from Publication III.

visual web user interface for the DT documents, shown in Figure 4.3b. Machine readability of the DT document was only tested by fetching its contents to the user interface, but the DT document was identified as a possible tool for describing how to connect to DT building blocks. The experimentation indicates that an iterative standardization process must be initiated before DT documents can be used more widely.

4.3.2 Basic principles of Digital Twin Web

Digital Twin Web (DTW), also referred to as Twinweb, was defined as "an ongoing development effort for creating a global network of digital twins in a similar internet-native and user-friendly manner as the World Wide Web (WWW) provides information to people" [4]. Twinweb embraces both human and machine readability. The twins include descriptions of how they are related to other twins, forming a knowledge network of the real world.

Twinweb uses DT documents as descriptions of twins and needs some kind of agreed protocol to exchange these documents. Both the basic structure and the protocol need to be standardized before Twinweb can be used efficiently. The main standard development effort of Publication III was to publish an initial draft for the DT document standard in GitHub [5].

4.3.3 Validating the data link approach of FDTF

Both the digital twin document and the API gateway are implementations of the data linking approach presented earlier in FDTF, although they are located on different information layers. The DT document concentrates on describing meta-level information about the twin, i.e., data about the data, while the API gateway makes the actual data from multiple DT blocks available from a single API.

The two approaches were presented separately but would benefit from being merged into one solution. Specifically, each API gateway could be set up with information found from the corresponding DT document. The API gateway information needs to be described in a uniform way, showing a concrete example of a need for DT document standardization.

4.4 Twinbase

Earlier publications had shown a need for a method for combining digital twin building blocks together and presented digital twin documents as a solution for that. Publication IV enables the scalable distribution of digital twin documents with three main results:

1. Introduction of Twinbase as a user-friendly platform for distributing

digital twin documents.
2. Formalization of the general structure of the Digital Twin Web.
3. Defining the concept of DTID registry as a component of the Digital Twin Web.

These three main results are enabled and evaluated by two supporting contributions:

4. Describing Git-based architecture for digital twins (GADIT) as a general method for building Git-based DT document distribution servers.
5. Performing initial measurements to assess the applicability of the presented approach.

Additionally, Publication IV introduced four openly accessible resources shown in Table 4.1.

Table 4.1. Openly accessible resources introduced in Publication IV.

Resource	Available at
Twinbase source code	`https://github.com/twinbase/twinbase`
Twinbase demo server	`https://dtw.twinbase.org`
DTWeb python library	"dtweb" via pip or `https://github.com/juusoautiosalo/dtweb-python`
Python scripts for performance measurements	`https://github.com/juusoautiosalo/dtweb-measurements`

4.4.1 Twinbase

Twinbase is an open-source server software for the Digital Twin Web, developed by the author. The main purpose of Twinbase is to distribute DT documents from owners to users, as shown in Figure 4.4. The DT document

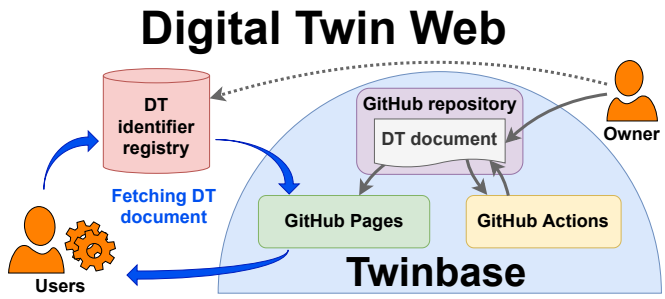


Figure 4.4. Twinbase enables distributing digital twin documents from owners to users, acting as a Digital Twin Web server. Reprinted from Publication IV.

owners store the documents in a Git repository, which also handles version

control of the documents. The documents and their supporting files are modified by Git workflows. The DT documents are distributed to users via a static web server that fetches its contents from the Git repository. Users find the static web server via digital twin identifier registries (Section 4.4.3) as defined by the structure of Digital Twin Web (Section 4.4.2).

Thanks to the GADIT architecture (Section 4.4.4), Twinbase can be hosted by free-of-charge GitHub services directly from a GitHub repository. Twinbase is permissibly licensed, so a new Twinbase instance can be set up by copying its source code according to the instructions found on its readme description at `https://github.com/twinbase/twinbase`.

Distributing DT documents is the single purpose Twinbase exists, and all functions of Twinbase revolve around making the management of DT documents effortless. Using free-of-charge GitHub services by default allows new users to publish their digital twins on the internet even if they have no experience in server administration and no willingness to invest money in their experiment. The web server makes reading the documents easier.

4.4.2 Structure of Digital Twin Web

The basic structure of Digital Twin Web had to be defined before a Digital Twin Web server, such as Twinbase, could find its final form. The structure is shown in Figure 4.4, although instead of being limited to using Twinbase and GitHub services, digital twin documents can also be served from other types of Digital Twin Web server software. However, the structure is currently only a proposal and should be validated and improved according to what works in practical development.

According to the proposed structure, the Digital Twin Web consists of a digital twin identifier (DTID) registries and DTW servers. Users fetch a DT document by first asking for the location of the document from a DTID registry and then fetching the document from the server. The owner of a digital twin owns and modifies both the DT registry entry and the DT document for that digital twin.

4.4.3 Digital twin identifier registry

Digital twin identifier (DTID) registry, also referred to as a *Twin ID* registry, is a database that records the ownership of Twin IDs and redirects users to the hosting locations of the corresponding twin documents. The IDs provided by Twin ID registries are permanent, globally accessible, and transferable, answering the specific needs that the digital twin concept has due to its positioning between the real and virtual worlds.

The functionality of Twin ID registries is similar to how the Domain Name System (DNS) is used in WWW, although Twin IDs are used for

individual twins whereas WWW uses DNS for domain names that correspond to whole sites. The dissimilarity of the use cases creates a difference between how many Twin IDs and domain names are needed. A large corporation can cope with one domain name, but it may need tens of thousands or even millions of Twin IDs for all of its devices and components, so the number of needed Twin IDs can be expected to be much higher than the number of needed domain names.

The Twin ID registry is at an early concept stage, and its specifics should be defined via further exploration. The basic redirecting functionality of a Twin ID registry could be achieved with regular URL (Uniform Resource Locator) redirection services. The redirection was a large source of variation for the overall response times of twin documents in the performance measurements of section 4.4.5.

4.4.4 Git-based architecture for digital twins (GADIT)

GADIT (Git-based architecture for digital twins) is an architecture style for implementing a Digital Twin Web server with Git repository and its two common peripherals: a CI (continuous integration) system and a static web server. GADIT assumes that there is a separate Twin ID registry that handles the IDs of twins, and the registry is not a part of a GADIT server.

Twinbase follows the GADIT architecture, so the structure of Twinbase in Figure 4.4 corresponds to the structure of GADIT. However, GADIT is more general than Twinbase. Instead of a GitHub repository, GADIT servers can use any Git repository that has the required integration possibilities to the other components. In place of GitHub Actions, GADIT systems can leverage any Git CI workflow solution that can be integrated into the Git repository. And instead of GitHub Pages, any static web server can be used if it can be set up to serve the contents of the Git repository.

All GADIT implementations should follow the same digital twin document standards, at least to the user-facing side, although GADIT implementation can leverage specific fields in the document. All GADIT implementations should also be able to be used with any Twin ID registries, although there can be special integration solutions that help the management of Twin IDs between certain registries and Twinweb server implementations.

There are some Git solutions that can be used for GADIT with fairly small effort. E.g., GitLab provides the same integration possibilities on its free-of-charge offering, although the CI system must be hosted somewhere else. GitLab also includes a permissibly licensed open-source version that can enable the deployment of new self-hosted Twinbase instances through future development.

4.4.5 Performance measurements

Selected performance measurements were implemented to validate the basic feasibility of the Digital Twin Web and Twinbase approaches. An important measure for users is the response time from sending a query with the Twin ID until receiving a DT document. We measured the response times in two cases: fetching a single DT document and fetching six networked documents sequentially based on the relations described in the documents. The measurement for fetching the single document was implemented for eight different registries, from which three registries were selected for the network measurements. All of the documents were fetched from the same Twinbase hosted at `https://juusoautiosalo.github.io/twinbase-for-measurements/`. The sample size was 1000 for each registry in both measurements. Further specifics of the measurements can be examined from the source code available at `https://github.com/juusoautiosalo/dtweb-measurements`.

The total response time consists of the response time of the Twin ID registry and the response time of the static web server of Twinbase. The measurement scripts recorded each of these response times separately, but the static web server gave such steady results at approximately 0.1 seconds that it was not distinguished the results. Only one static web server (GitHub Pages) was used for the measurements, as also two other static web servers (Domainhotelli and users.aalto.fi) showed a similar response time of approximately 0.1 seconds in preliminary tests. A deeper examination of the routes of the queries should be implemented to reach conclusive results of systemic performance, but the conducted measurements already give a good general indication of usability.

The response times for fetching a single document are shown in Figure 4.5. The results show that there is a significant and consistent deviation between the response times of the measured Twin ID registries. The means ranged from approximately 0.4 seconds to approximately 1.1 seconds. The response time of different samples of each registry deviated in time windows of 0.4 to 0.6 seconds for the first 99% of the samples.

The response times for fetching six networked DT documents are shown in Figure 4.6. The results demonstrate that the differences identified in single document fetching may make a difference between a barely feasible median fetch time of 2.0 seconds for d-t.fi and a completely impractical fetch time of 6.8 seconds for w3id.org for the sixth document.

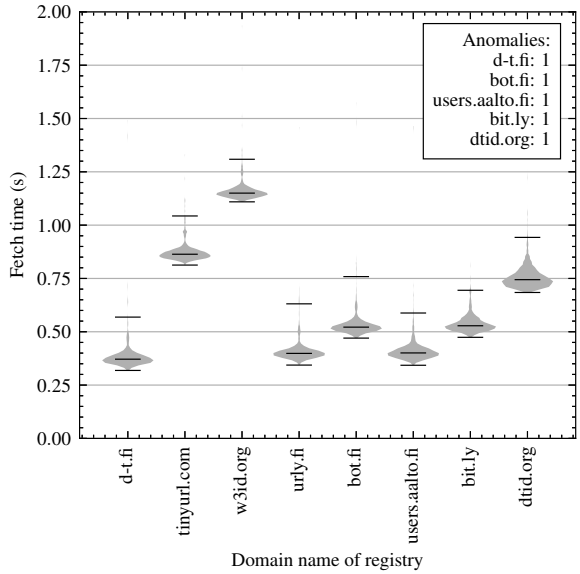


Figure 4.5. Response times for fetching a DT document from Twinbase via eight DTID registries. The results show that there is significant and consistent variation between the response times of the used DTID registries. Anomalies refer to response times of over 2.0 seconds. The sample size was 1000 for each registry, constituting a total of 8000 samples. Reprinted from Publication IV.

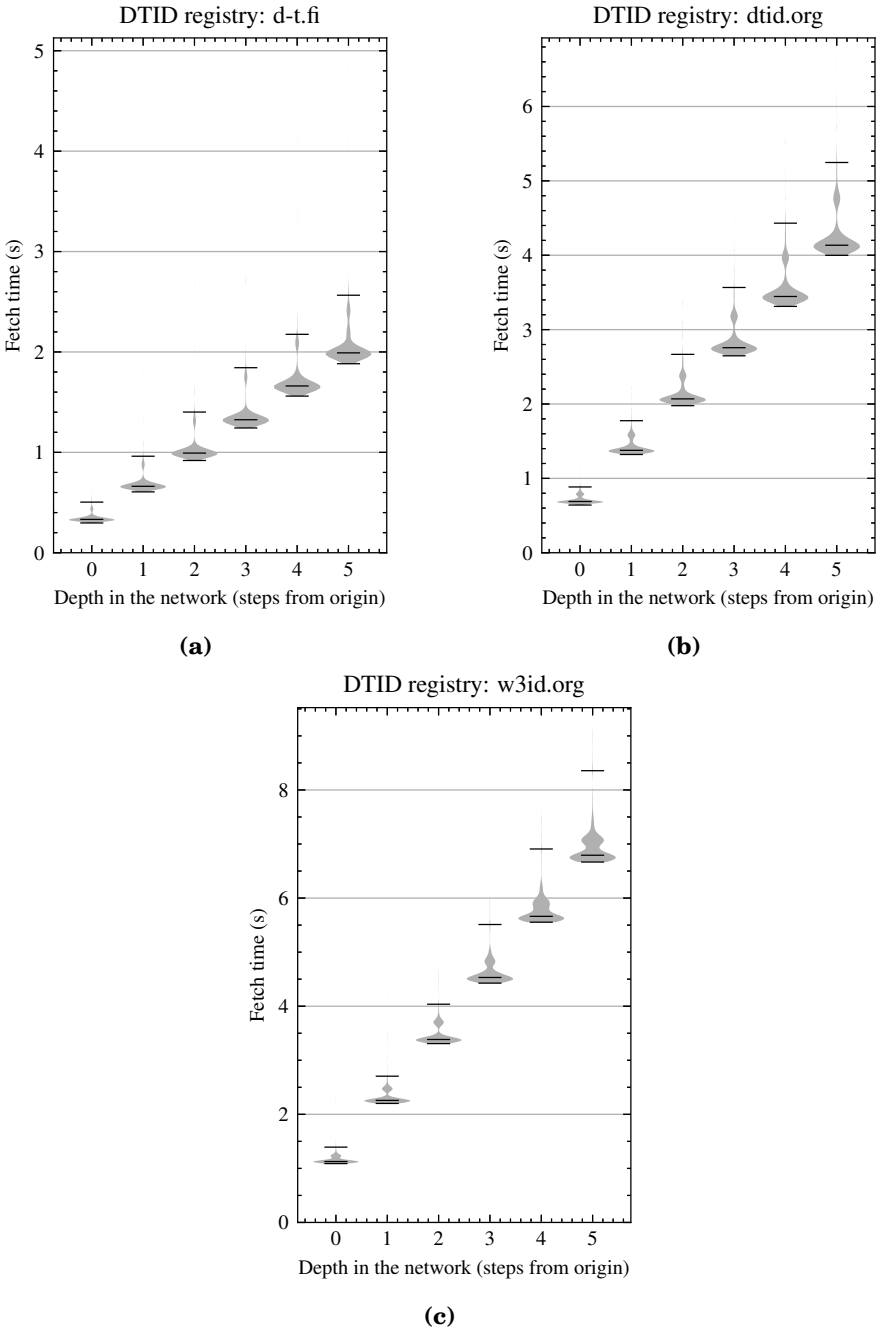


Figure 4.6. Response times for fetching six networked DT documents consecutively via three DTID registries. The results demonstrate that a recursive fetch of six documents is barely feasible with the fastest registry (a) and unmanageably slow with the slowest (c). The sample size was 1000 for each document, constituting 6000 fetches for each registry and a total of 18000 samples. Reprinted from Publication IV.

5. Discussion

In this chapter, I discuss the results one by one, examine the research methods, answer the research questions, provide a general outlook on the future of digital twins, and present recommendations for future research.

5.1 Discussion of results

This dissertation describes a path from not knowing what digital twins are to presenting a set of solutions to make scalable digital twins. The journey started with a combination of conceptual and practical development efforts that showed a fundamental discrepancy between how digital twins could and should be implemented. Especially, there were no clear methods to integrate digital twin components to each other even though a digital twin should provide all lifecycle data of its real-world counterpart. The discrepancy led to the technical development of a data link that would combine digital twin components together with two methods: bringing several twin-component APIs behind one API and describing the whole twin and its components in a digital twin document. The document approach seemed to have more undiscovered potential, and other practitioners also used it. Hence, the final work was to create a user-friendly platform for distributing public digital twin documents, an effort I expect to help develop specifications for that document.

5.1.1 Feature-based framework

The feature-based digital twin framework consists of several components that help understand the digital twin concept more deeply, which also has practical implications. Looking at digital twins from a feature perspective makes it apparent why twins can be so different from each other. If features are selected only to serve the use case of the twin, it is possible to have twins that have no overlapping features. The features also help to evaluate the compatibility of software for your use case: you can start by defining

what features you need and then select the software that fulfills those criteria.

The framework uses the notion of digital twin building blocks, which are software that can be connected to each other via interfaces to form a multi-component digital twin. If making new combinations is effortless enough, the multi-component twins can be called modular digital twins, indicating that the twins are even supposed to be assembled modularly from components instead of making customized one-off twins for every use case.

However, integration of software is an age-old problem, relentlessly creating problems even in modern software. The feature-based framework suggests a special feature, "data link", to make integration more managed and approachable. The suggestion was purely conceptual in the framework, but as the case study of Publication II confirmed the importance of effortless integration, practical development of the data link concept was selected as the main topic for Publication III. The data link approach was developed further also in Publication IV.

Even though the framework was a theoretical exploration of the nature of digital twins, it still provided valuable support in designing the directions for practical research. Hence, the framework can be seen as a *good theory* when evaluated through the lenses of Lewin's maxim "there is nothing so practical as a good theory" [72].

5.1.2 Case study on Ilmatar crane

The case study provided valuable practical insight into the development process of a digital twin of an industrial machine. The development included multiple teams that developed several end-user applications for the crane. Creating an integrated twin seemed possible when there was a deliberate attempt and cross-organizational leadership towards integration, but when left to develop naturally, the teams created their own custom solutions, and the twin manifested in separate components. Overall, the case study indicates that an integrated digital twin will not happen with the current tools and processes, suggesting that something is missing from the digital twin technology stack.

Even though most of the crane data were acquired from a single source, the OPC UA interface of the crane, the end-user applications were still a bunch of separate software components. Integrated twins need integration in both ends of the twin data pipeline: at the start and at the end. And perhaps also in the middle to help the development process.

APIs proved to be excellent tools for building use case-specific digital twin applications. The applications typically required at least three basic components: acquiring data, processing data, and providing a user interface. These components were often implemented in different software

systems, necessitating the use of APIs. The best development efficiency was achieved when suitable APIs were available before the work was initiated, but also newly acquired APIs enabled the creation of case-specific twin applications. It was also noticed that existing APIs were not useful if they did not fit the use case and the skills of the developers.

Taking part in the practical development efforts, each consisting of dozens or hundreds of hours of work collectively, allowed me to observe in depth what worked and what did not. I also saw what kind of resources accelerated development work and how missing resources made it extremely difficult even to start development. Development was very quick when the application could be planned well in advance, but the planners had to have deep enough knowledge about existing resources. It was especially essential to know if the existing APIs would fit together.

Overall, the case study showed that attempting to develop data-focused digital twins with the current tools was a fool's errand, and something had to be done to get out of the mess. The solution seemed to lie in integrating the different components with standardized APIs.

5.1.3 Digital twin document

The data link implementation of Publication III included both an API gateway for a digital twin and an initial draft for a digital twin document specification. The API gateway provides direct technical aid to the management of APIs of the different components of a digital twin, whereas the twin document attempts to be a more general meta-level solution that allows defining digital twins more uniformly. These two approaches can support each other in further development efforts, but the digital twin document was chosen as the focus of this dissertation.

The development of the digital twin document specification was initiated without the knowledge of other similar specifications. However, during the development, DTDL (Digital Twins Definition Language) and WoT TD (Web of Things Thing Description) were identified as relevant formats, but they did not fill some of the requirements we set for the digital twin document, so we decided to proceed with making our own proposal and attempting to merge the approaches later. Simultaneously, Jacoby and Usländer published a review of these and other relevant specifications [60], from which especially AAS (Asset Administration Shell) and NGSI-LD (Next Generation Service Interfaces - Linked Data) are worth mentioning.

All of the mentioned specifications have their own user groups and serve their own specific purposes. The specifications are partly overlapping, but each of them seems to contain some part that is not available in the other specifications. All of them also share the same linked data standards as a base and can be written in JSON-LD (JavaScript Object Notation for Linked Data) format and other similar formats. The amount of information

from all of those specifications is overwhelming, and it is unfortunate that users must make compromises only because the specifications are fragmented. Hence, we aim to violently include all other relevant specifications into the DT document specification. We also aim to make a digital twin-targeted specification in contrast to some of the more general approaches. We will also consider transferring our development efforts to another specification if one fulfills our criteria well enough. However, integration work will be required in any case because the existing specifications have already started to diverge.

Developing a comprehensive digital twin document specification will be a massive effort, and all help is well appreciated. You can help, e.g., by opening an issue at `https://github.com/AaltoIIC/dt-document` to point out the need for support for your use case. The actual specification work is yet to be started properly, so even the very basics are open for discussion and expected to change. We hope to collect a diverse enough set of use cases so that we end up with a non-domain-specific digital twin specification.

5.1.4 Twinbase

The conceptual development of Twinbase was initiated by a need to easily create an internet-accessible master data pointer, i.e., a data link, for digital twins. However, the actual development was not started until GADIT (Git-based architecture for digital twins) was invented because I did not want to create another cloud platform that would require extensive server administration and would therefore be out of reach for most domain-oriented digital twin developers. The GADIT architecture was enabled by the observation in Publication III that a text-only file, i.e., a DT document, can be a useful component for the future development of digital twins. And specifically, it should be effortless to distribute these text-only files via the internet.

Twinbase was developed as a public-first open-source project to promote the adoption and, therefore, the development of digital twin documents. I also expect that the public network of digital twins will form a fruitful reference environment for the development of private twins, similarly as public WWW pages have been a breeding ground for private WWW solutions such as online banking.

It is evident that a private method for deploying Twinbase is needed soon. Creating a private version should not be too difficult as all components of GADIT can be deployed privately with existing software solutions. Nevertheless, I intend to keep sharing Digital Twin Web materials publicly as much as possible while ensuring compliance with security, privacy, and confidentiality requirements. If Tim Berners-Lee had developed his World Wide Web solutions only privately instead of sharing them publicly, we probably would not have the internet we have today.

There is a risk that Twinbase will become just another platform among the already extensive amount of cloud platforms. However, Twinbase is different from most other platforms in at least three aspects. First, Twinbase can be hosted on services that require so minimal amount of server capacity that some commercial providers offer them free-of-charge. Hence, the upkeep costs of Twinbase can be close to zero. There is a risk that GitHub will change its payment models, but Twinbase can be modified to allow self-hosting with the open-source version of GitLab, keeping costs low and ensuring independence.

Second, Twinbase is foremost an integration platform, storing mainly metadata instead of actual data. Twinbase focuses on the quality of integration and leaves the quality of actual data and applications to other platforms. As an independent open-source software project, Twinbase supports other platforms equally well and, therefore, avoids vendor lock-in. For example, whereas some cloud platforms may provide metadata only for the data that they contain, Twinbase focuses on the quality of metadata wherever the actual data is located.

Third, Twinbase is solely a digital twin platform. It focuses on solving digital twin problems, leaving out any potential clutter and limitations introduced by support for other purposes.

The focus on meta-level information is also a threat to the adoption of Twinbase and the whole Digital Twin Web because the efficient use of meta-level solutions seems to require a certain mindset or set of knowledge that is difficult to acquire. Simply put, it is difficult to explain why Twinbase and its digital twin documents are needed. However, different types of digital twin documents have been deemed necessary by so many independent development communities that their necessity seems unavoidable. The necessity will make them widely adopted, and their purpose will become more apparent.

Twinbase is not yet a proper production-ready platform, but it is ready for development-focused use that includes fixing and improving the platform on the go. The parallel development with the digital twin document specifications will likely make the development of both of those a messy process, at least in the beginning. Best practices should be developed and shared on the go; for example, the parallel development may pose a need for separate production and development instances of Twinbase, such as `https://aaltoiic.twinbase.org` and `https://aaltoiic-dev.twinbase.org`.

The performance measurements demonstrated the basic functionality of Twinbase and the whole Digital Twin Web approach, providing initial validation that the concepts work as intended. The numerical values of the measurements provide a baseline from where to start performance improvements that will be required for advanced use cases, such as searching for a specific sensor type from a network of nested twin documents.

5.1.5 Summary of results

The most certain result is that the existing tools and technologies did not support creating scalable digital twin networks. The core of digital twins has not yet been put into technology, let alone a user-friendly tool, that would allow the seamless integration required for scalability. Instead, the integrations had to be done as laborious one-off projects. The data link approach of FDTF attempts to overcome this issue, but it could not be validated conclusively. Currently, the data link approach acts as a general framework for digital twin development, hoping to be validated via further studies and practical implementation. The two last publications concentrated on developing the data link concept into a technology that could be used in later development. The DT document approach was supported by several other sources, and it seems that the fundamentals of digital twins have been found. The core of digital twin technology will most likely be a linked data document that describes a digital twin. However, this is only qualitative insight and should be validated by observing future digital twin implementations. In the future, the DT document approach can be regarded as the authoritative digital twin technology if a clear majority of digital twin implementations will leverage some form of DT documents.

5.2 Methodological considerations

The set of three research methods used for this dissertation, Grounded Theory, participatory action research (PAR), and design science, can be regarded as challenging as they differ from the quantitative methods traditionally used in the mechanical engineering discipline. They were also challenging because I had not used the methods before starting the dissertation, with the exception of using PAR as part of the team [126] at the inception of the dissertation process. Perhaps due to my inexperience with the methods, I used them primarily as general guidelines rather than strictly following their procedures by the book.

The used methods seemed to support both each other and the research topic. Digital twin was a new topic, and not much existing research was available when the research process started. Especially, fundamental theories had not been established outside the basic concept, which indicated that an explorative research approach such as Grounded Theory could help form the initial hypotheses. The approach produced the feature-based digital twin framework, which proved to be helpful for the later studies. In further support of the Grounded Theory approach, also two other publications ended up using the Grounded Theory methodology to form initial digital twin categorizations [63, 141].

PAR was an appropriate method for the case study, and coupling it with Grounded Theory was an appropriate choice for drawing conclusions from the experiences. The two methods worked nicely together during the first phase of the dissertation process as the two publications were worked on mainly in parallel. The methods were able to produce a good set of hypothetical theories that had to be further validated through practical experimentation.

After the initial hypotheses had been formed, the research approach had to be changed into one that could support the exploration of the hypotheses. The design science method acted as an appropriate framework for creating and evaluating the produced software artifacts.

The traditional scientific method consists of approximately these steps: *question, research, hypothesis, experiment, analysis,* and *conclusion*. When assessing the overall process of this dissertation from the traditional method, we can observe that the two first publications concentrated mainly on background *research* and *hypothesis* generation, as is typical for a Grounded Theory-based research process. (In fact, Grounded Theory is fundamentally different from the traditional method as it generates hypotheses or theories instead of attempting to verify them.) The two latter publications follow design science to concentrate on the *experiment* phase while providing some tools for *analyzing* the designs. The last publication also gives some *concluding* remarks on the future development of digital twins, although the primary *conclusion* is done in this summary part of the dissertation.

Now that all the phases of the whole scientific method process have been explored in the light of the feature-based digital twin framework, it should be possible to accelerate the traditional cycle into shorter intervals. Fitting the whole process of the scientific method into one research article should become feasible. However, these can only study some targeted parts of the Digital Twin Web approach, whereas the whole approach can be analyzed appropriately only via several years of combined research and practical implementation efforts.

The original research plan for this dissertation consisted of three main bodies of work: defining digital twin, building a case example of a digital twin for the Ilmatar crane, and developing digital twin-based machine design methods. The first two were conducted successfully, but new machine design methods were not developed for two main reasons. First, a similar conceptual study was published [133] during the case study. Second, the case study also showed that digital twins were not yet convenient enough tools for concrete methodological development. (The case study did include work towards new machine design methods, but I could not see a pathway towards generalizing them.) Instead, the third phase of the dissertation concentrated on developing digital twins into a tool that could be leveraged for developing machine design methods in later work.

In conclusion, the research methods supported the dissertation work as the digital twin concept itself could not be used as a tool for conducting academic research. Grounded Theory may not be needed anymore as the basic theories have been formed, although there might still be room for discoveries. PAR seems like an appropriate method for gaining deep insight into actual digital twin development in the future. Design science seems like a promising method for experimenting with targeted aspects of the digital twin ecosystem. This dissertation introduced some new methodological discoveries for the digital twin concept, and they are now moving into a further evaluation phase.

5.3 Research questions and answers

In this section, I answer the research questions RQ1-RQ3 one by one.

RQ1: What is a digital twin?

Publication I gives a two-sentence definition: "Digital twin is a virtual entity that is linked to a real-world entity. Digital twin consists of various features that are selected and customized to serve the needs of diverse use cases." In contrast to many other definitions in the literature, this definition does not reflect any particular use case or domain. The first sentence attempts to capture the basic essence of the digital twin concept illustrated by Grieves in 2002 [47] and the second sentence emphasizes that digital twins are custom-built and therefore different from each other.

The definition leverages the overall observation that digital twins consist of several features. The dissertation also tried to find out what are the essential features, but the process was not robust enough to define the features conclusively. Instead, developing a method for combining the features of different twin components seems to have more practical implications. The digital twin description documents used in this dissertation suggest defining each digital twin through its description document: a twin consists only of the components mentioned in the document.

As a further observation during the latter part of the work, it seems that the contents of digital twins can be categorized into two main classes in regard to their relation to the real world: some contents concentrate on dutifully describing the corresponding real-world entity, while others provide additional services that go beyond mere description, such as predictive maintenance alerts, simulations of behavior in extraordinary circumstances, and user training.

RQ2: How to build a digital twin?

The results suggest building digital twins by assembling them from building blocks that are appropriate for the use case of that digital twin. The feature-based digital twin framework includes a general step-by-step procedure for creating digital twins in subsection 4.1.4. The details of the procedure are not yet fully developed, although we propose the *digital twin document* (presented in subsection 4.3.1) as the master method of combining the building blocks together into one twin. Digital twin documents only contain static information, so for a more dynamic integration, other integration methods such as an API gateway can be leveraged.

RQ3: How to build a network of digital twins?

The question consists of two parts: 1) how to be able to make a lot of twins, and 2) how to combine them together into a network.

A lot of digital twins can be made by initializing a digital twin description document for each twin as part of the business process of its real-world counterpart. The actual building blocks of the twin are added as links to that document according to needs, leading to a fit-for-purpose twin. Using the twin document as the master description of the twin prevents users from creating duplicate information. Initializing and adding/proposing new elements to the description document must be an effortless and integral part of the business processes of the real-world counterparts, and this is possible only with a flexible approach such as a twin document that is available via the internet. Twinbase is a practical prototype of a digital twin document distribution system that enables integration into business processes via a user-friendly human interface and potential for machine client integration. However, a private version of Twinbase needs to be developed before it can be used for production twins that contain confidential information.

Digital twins can be combined together into a network by describing each twin's relations to other relevant twins in its description document. The relations are included as semantic links to the other twins, so users can conveniently browse through related twins. For two-way access, the relation between the two twins must be described in both twin documents.

5.4 Digital Twin Web

Currently, Digital Twin Web is more of a long-term initiative than a robust scientific result. It is an aggregation of the other results, and the primary suggested theme for future research. The basic principles and structure of DTW were included in Publication III and Publication IV, respectively, but it should still face more targeted scientific scrutiny. And especially, DTW should be validated in practical use cases.

The idea of the Digital Twin Web started forming around the midway of this dissertation. The basic idea is a network of digital twins that mirrors the networked real world so that digital information of the real world is more easily accessible through digital methods. Simply put, DTW connects internet resources to their real-world counterparts. However, these internet resources, or digital twin building blocks, are still heavily under development.

At some point, the Digital Twin Web should get more integrated into the three dimensions of the physical world through augmented and virtual reality technologies. To achieve this, it might be appropriate to merge DTW with the metaverse initiatives of major tech companies [20] and other development communities [149]. As a more immediate approach, digital twin documents could be integrated into existing industrial applications, such as the mixed reality control application for the Ilmatar crane [57, 137].

I expect the Digital Twin Web ecosystem to be formed roughly from the following technology stack: Twin ID registries, digital twin document platforms, and twin application platforms. Twin ID registries keep track of the identifiers of the twins, twin document platforms host the twin documents behind the IDs, and twin application platforms enable the creation of individual applications that leverage the information from the twin documents. Currently, Twinbase is a working proof-of-concept stage DT document platform, and there are several potential twin application platforms available, but the Twin ID registry concept still seems to require some fundamental research.

5.5 General outlook on the future of digital twins

In this section, I describe my estimations or prophecies on what the future of digital twins will look like. I don't give a timeline for the prophecies but rather describe things that I think will happen at some point, be it a year or twenty years from now. However, it seems that the development can be hastened collectively by making publicly available digital twin technologies and implementations.

The Hype Cycle by Gartner [36] can be a useful method for predicting the future of technological trends. At the start of this thesis work in 2017, the digital twin term was passing from *innovation trigger* phase to *peak of inflated expectations* [94], reaching the peak in 2018 [95]. The 2019 cycle [96] did not mention digital twins but in the 2020 cycle [97], "digital twin of the person" and "citizen twin" appear in the boundary of *innovation trigger* and *peak of inflated expectations*. The 2021 cycle [98] again does not mention digital twins, but from my own estimation, the digital twin concept seems to have moved *through the disillusionment* and is now in the *slope of enlightenment* phase, meaning we have now made enough failed digital

twin experiments and found a sustainable approach for creating digital twins. The approach, i.e., the general method of digital twin description document, is still heavily under development, but we are now on track to reach the *plateau of productivity*. However, reaching the plateau requires global standardization efforts, which need to be funded somehow.

It seems that a global network of digital twins is destined to happen at some point. It may not be called the "Digital Twin Web" as proposed in this dissertation, but it seems quite certain that there will be some kind of network akin to Twinweb. I expect this network to be an open platform where digital twins from different providers collaborate with each other, much like the World Wide Web is open for all entrants. However, the close tie to the real world potentially makes the implementation of DTW very complex, so achieving an open digital twin business environment might take four or forty years or something between.

Until the very last few years, commercial tools for the implementation of modular digital twins have practically not existed. Now one strong entrant, Azure Digital Twins, has appeared, and hopefully, others will follow. An open-source platform such as Twinbase may be useful for sparking up the competition and may provide a faster transition toward an open business environment.

According to my experience during the dissertation work, the user-friendliness of digital twin development tools proved essential. While big enterprises may have resources to cope with difficult tools for important tasks, I firmly believe that a proper global network of digital twins can only be accomplished if the creation of twins is similarly effortless and enticing as the creation of web pages was in the early 90s. Twin developers need to be able to move fast and let their creative vibes flourish so that they can develop end-user applications and platforms that are similarly easy to use and even addictive as social media platforms such as Facebook. What is difficult is that we are not really able to see what the killer applications of the Digital Twin Web will be, so right now, we just need to create the basics as a general platform and trust that the benefit will come. In my opinion, the promise of the Internet of Things and digital twins is so transformative that benefits must arrive one way or another. Right now, the internet is a place for people only, and we need to open it up for machines as well.

At some point, the definition of digital twin might get more technical. If the digital twin document approach gets prominent, the definition might turn into "Digital twin is a virtual entity that is defined in a twin document and linked to a real-world entity."

5.6 Future work

The dissertation work started out in an area full of research gaps. Some suggestions to solve the gaps were proposed, but new needs were found for both research and practical development. Researchers can provide answers to practical questions that directly accelerate development efforts, fundamental theoretical questions that can help us make the right choices in the long term, or something in between. Still, the Digital Twin Web can only be built by building it.

Many practical challenges need to be solved before networked digital twins start providing the network benefits they are destined to yield at some point. Researchers can help, for example, by finding answers to these practically oriented research questions:

1. How to create a digital twin description format that works across digital twin platforms of all vendors?
2. How to integrate existing digital twin description formats into one uniform solution?
3. What are the required, recommended, and optional elements of a general information model for digital twins?
4. How to integrate domain and application-specific content to digital twin documents?
5. How to integrate external content to digital twin documents?
6. What kind of developer tools best support building the Digital Twin Web?
7. How to establish an internet-wide digital twin identification system?
8. What is a sufficient response time for fetching a digital twin document?
9. How to scale the discovery of digital twin contents from the internet and from physical spaces?
10. How to couple real-world things to digital twins in a user-friendly and scalable way?
11. How to scale the creation and maintenance of 3D models of physical things?
12. What kinds of added value do networked digital twins provide in real-life use cases?
13. How to make the creation of digital twin documents economically profitable?

The questions span several essential areas, but some topics are surely missing, and new challenges are sure to follow. Nevertheless, answering these should provide a flying start for building the Digital Twin Web. Experimentation should be an efficient method for finding answers to many of the questions.

Digital Twin Web is a promising approach but has not yet been described

comprehensively. (In the articles of this dissertation, DTW was described only to support the data link implementation and the Twinbase software.) The comprehensive description should reveal the whole big picture of DTW and form a roadmap for future efforts, such as developing standards, software, and protocols. The roadmap and the related documentation should be reader-friendly also for practitioners so that practical development can start efficiently. In addition to the Digital Twin Web roadmap, I plan to write a theoretical article on the information contents of things and twins to help establish a more fundamental understanding of the nature of digital twins.

Finding good enough ways for building networks of digital twins remains a fundamentally important research topic. Any newfound good practices can become subjects of standardization, leading to these three research questions: *What should be standardized? What are the layers of standardization? How should the standards be related to each other?* Researchers should be solving these types of questions to support the decision-making processes of standardization, while the standardization processes should probably be administered by standardization organizations and serve the needs of digital twin practitioners.

Developing digital twin software per se is not a topic for academic research in most cases. However, developing proof-of-concept software can play a crucial part in DTW development thanks to the power of its "show, don't tell" effect. The software can be evaluated with design science methodologies. Also, the processes of developing digital twin software could be researched: *What are the best methodologies for developing digital twin software?* Up to the current point, proprietary software has shown the most advanced results, but recently, a significant portion of both researchers and practitioners have started rooting for the benefits of open-source software. Fruitful research subjects could include the ecosystems of iTwin.js [14], Eclipse Ditto [34], and Digital Twin Definition Language [28].

Open-source software is yet to find proper business models that directly ensure the longevity of the software project. Instead, open-source software projects are traditionally maintained by voluntary contributors or companies that get their paychecks from somewhere else. The following questions could be researched to make open-source software more prevalent: *How to develop open-source software as efficiently as possible? How could user needs direct the development of open-source software? How could the added value received by open-source software users be leveraged to accelerate the development?* Open-source developers need to eat too, so getting money flowing around open source would probably accelerate the development. Potential study subjects include GitHub Sponsors [39], Open Collective [92], and Gitcoin [38]. Another option could be an enhancement-based crowdfunding model we are developing at Plate Funding Oy [9]. Also, universities could have special roles in some open-source ecosystems

thanks to their neutrality and direct access to new talent.

The future directions of Digital Twin Web development could be assessed according to the participatory foresight research methodologies described by Kaivo-Oja [65]. For example, the relation between the DTW and metaverse initiatives might be an exciting research direction.

6. Conclusion

This dissertation introduces the Digital Twin Web (DTW) approach for building a global network of digital twins. The approach claims that using intelligently standardized text documents as the core of digital twins can provide a transformative enhancement to the interconnectedness of the physical and digital worlds. DTW is both human and machine-readable and draws methodological inspiration from the success of the World Wide Web.

The Digital Twin Web is based on the four main scientific contributions of this dissertation:

1. **Feature-based digital twin framework** for creating modular digital twins.
2. **Lessons learned from a case study** on the development of an industrial multi-component twin.
3. **Demonstration of the data link** feature of the framework with a "digital twin document".
4. **Twinbase** as **open-source server software** for hosting digital twin documents.

The feature-based digital twin framework states that digital twins consist of conceptual features implemented by actual software building blocks. The blocks are connected to each other with interfaces administered by a particular "data link" feature. The framework forms a roadmap towards building modular digital twins according to user needs rather than the capabilities of software packages.

The case study presents and analyzes the development efforts for the digital twin of the overhead crane "Ilmatar". The twin of the crane was implemented in one large and several small projects by various teams and manifested itself in singular applications that were not integrated into each other from the user perspective, even though each of the components had a data connection to the crane. The case showed that user-friendly APIs (application programming interfaces) were crucial for developing digital twin applications efficiently. Other critical technical factors accelerating digital

twin development were open-source software, open standards, and user-friendly tools in general. Also, non-technical factors proved essential with three standing out: purposeful use case (or a goal), cross-organizational leadership, and the appropriate skills of team members.

The demonstration of the framework concentrated on the technical implementation of the "data link" feature, introducing a draft specification of the "digital twin document". A twin document describes a digital twin in a human and machine-readable format, acting as a glue that ties the software components together. The format of the digital twin document should be specified as an iterative approach between practical and theoretical development efforts, leading to a standard way to describe a digital twin. Existing specifications, such as AAS, DTDL, WoT TD, and NGSI-LD, should be leveraged if possible.

Twinbase is a novel server software that enables publishing digital twin documents to the internet with free-of-charge GitHub services. It is a user-friendly example of *Digital Twin Web server software*. Twinbase consists of three main components: 1) a Git repository to store and track changes of the twin documents, 2) Git CI workflows to automate their modification, and 3) a static web server to distribute the documents to users. Future work should make Twinbase independent from any single vendor and enable hosting private twin documents.

A digital twin identifier (DTID) is the primary address of a digital twin and redirects user queries to the corresponding DTW server. The initial concept of the DTID registry was defined to provide permanent, globally accessible, and transferable identifiers for digital twins. Once DTID registries are fully developed, they are expected to take a similar position in DTW as the Domain Name System has in the World Wide Web (WWW).

The Digital Twin Web, also referred to as *Twinweb*, combines the previously mentioned contributions under a single approach and initiative. It shares several analogies with WWW but consists of digital twins, mirroring the real world more directly. The twins of Twinweb are described by digital twin documents similar to how HTML documents describe web pages. The development of the right kinds of standards and specifications is crucial for the success of Twinweb, and existing standards should be leveraged as much as possible. Essential topics for standardization include the format of the description documents, their semantics, and globally accessible identifiers for digital twins.

The research gaps identified for this dissertation were filled reasonably well. Digital Twin Web is an overall methodology for implementing a network of digital twins, and it is cross-sectoral by default. Twinbase is an open-source platform for web-based digital twins, although only for descriptions of the twins, i.e., digital twin documents. Standards for digital twins are too large a task to be tackled in one dissertation, but the Twinweb approach provides an overall roadmap towards standardization.

Users of digital twins, such as companies, governmental agencies, and citizens, can benefit from digital twins in countless ways thanks to their ability to leverage information as a replacement for wasted physical resources. Digital twins have suffered from poor scalability, but the methodologies introduced in this dissertation allow scaling both individual twins and networks of digital twins. The digital twin document is a central method for both directions, but it is still under development. Currently, building twins with a suitable existing twin description format seems like a good way to start enhancing the scalability of your digital twins. However, builders should acknowledge that finding the best format might be a project of its own, and the standards and specifications are developing fast. The Twinweb initiative aims for a user-centric approach by integrating the standards rather than developing new ones, although at least new integration practices must be introduced. Users can help the standardization processes by expressing specific or general needs, documenting use cases, or publishing twin descriptions.

For academics and the overall development of humanity, digital twins represent an opportunity to merge the digital and physical worlds. Until now, the research on digital twins and their technologies has been relying too much on one-off experiments that can not be replicated. We academics need to provide a roadmap for leveraging twins in the best possible ways. Luckily, the recent developments on open-source software and open standards seem to be starting a revolution towards a Digital Twin Web similarly as hypertext standards enabled the World Wide Web revolution. I believe these open development efforts will inevitably lead towards an integrated phygital world, materializing in a global network of digital twins akin to the Twinweb.

Building the Digital Twin Web will be a major effort and will require some coordination. As an initial method of coordination, I invite modifications to my digital twin document of the Earth, found via this twin identifier: `https://dtid.org/earth` [1]. I will use this twin as the grounding point for my public twin networks whenever feasible so that they can be discovered via the Earth twin. You are welcome to modify the description of the twin of Earth, add links to external resources about Earth, or add relations to twins of things that are related to Earth somehow. I reserve the right to approve, modify, or decline requests at will, although I will do my best to develop transparent practices over time.

The beginning will be messy; let's do it anyway!

[1] Please note that the identifier standards may change in the future, leading to a change of the twin identifier. I will do my best to provide redirection to my preferred twin of the Earth from this URL.

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