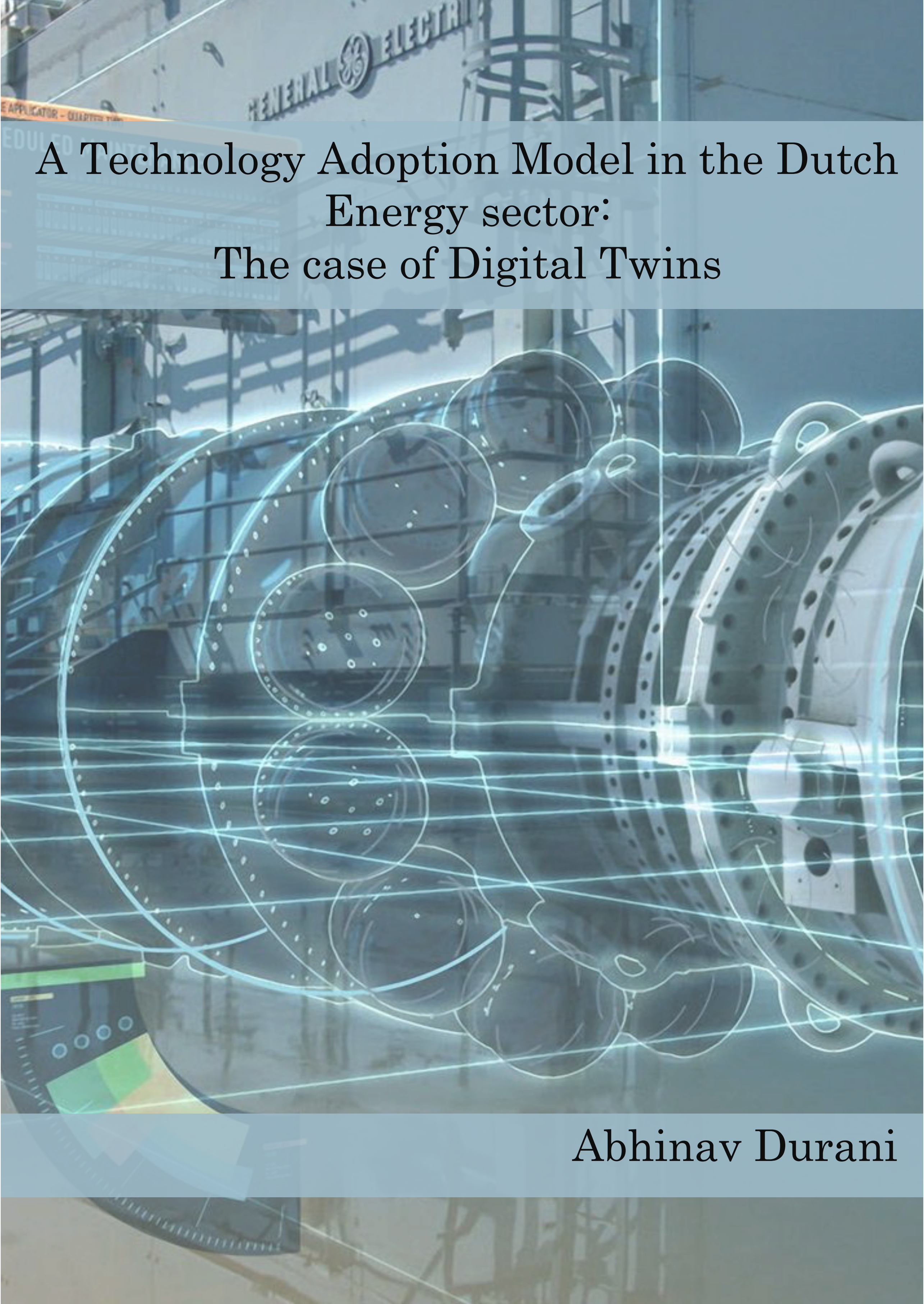
A Technology Adoption Model in the Dutch Energy sector: The case of Digital Twins



Abhinav Durani

A Technology Adoption Model in the Dutch Energy Sector: The case of Digital Twins

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Management of Technology**

Faculty of Technology, Policy and Management

by

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To be defended in public on 24th August 2021

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A TECHNOLOGY ADOPTION MODEL IN THE DUTCH ENERGY SECTOR

THE CASE OF DIGITAL TWINS

Master Thesis

A report submitted to the Delft University of Technology
in fulfillment of the requirements for the degree
MSc. Management of Technology
to be defended on 24th August 2021

by

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Satisfaction lies in the effort, not in the attainment

Mahatma Gandhi

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EXECUTIVE SUMMARY

Emerging technologies are revolutionizing organizational growth, productivity and investments more than ever before. One such technology that has come into the limelight in the past few years is the Digital Twin. The so-called 'digital twin' is a real-time virtual replica (representation) of any given physical asset/object. The full-potential of a digital twin lies in its ability to not only communicate with the physical asset, but also control it remotely. Although the concept of digital twins is more than a decade old, digital twin initiatives are now been deployed in the manufacturing, automotive and healthcare industries among others. One such industry, experimenting with digital twins is the Energy sector. The objective of this research was to perform an exploratory investigation into the adoption of Digital Twins in the Dutch Energy sector predominately by Transmission System Operators (TSOs) and Distribution System Operators (DSOs). The investigation comprised of four elements: establishing the most fitting technology adoption model when it comes to digital twins, determining the relevant adoption variables, exploring the perception of digital twins in the industry and investigating the relationship between absorptive capacity and organizational characteristics. The research method deployed for the former two elements was desk research, whereas the latter elements were probed by conducting (semi-structured) interviews and targeted questionnaires respectively. There were a total of nine participants involved in this research which included technology adoption decision-makers having a wide range of work experience (1-5 years to 20+ years) from the five of the eight TSO/DSOs of the Netherlands.

The research found that the most fitting technology adoption model when it comes to digital twins in the Dutch energy sector was the Technology-Organization-Environment (TOE) Framework with the following relevant (non-exhaustive) adoption variables: Complexity, Compatibility, Perception, Technological Characteristics, Availability, Organizational culture, Organizational size, Budget size, Incentives, Management support, Absorptive capacity, (decision-maker's) Demographics, Attitude towards technology, Regulations, Competitive pressure and Network effects. In addition, the overall perception of digital twins was found to be positive across the Dutch Energy sector, however, there was no consistent relationship established between organizational characteristics and the levels of digital twin perception. Similarly, the research suggested that organizational characteristics and absorptive capacity were not correlated. Nonetheless given the limitations of having a low number of study participants and the potential of bias amongst respondents towards their employer, the strength (significance) of these discovered relationships are indicative and should be further investigated in future research prior to making any additional claims that are conclusive.

PREFACE

This thesis describes the findings of the research carried out at the Faculty of Technology, Policy and Management in fulfillment of the requirements for the degree MSc. Management of Technology at the Delft University of Technology. The thesis is titled: "A Technology Adoption Model in the Dutch Energy Sector: The Case of Digital Twins" and contains less than 45.000 words. As a technology enthusiast, I have always been interested in how (emerging) technologies develop, evolve and advance over their lifetime. This underlying motivation led me to this research, where the factors relevant to the adoption of digital twins in the Dutch energy sector have been investigated. The importance of this work lies in applying a technology adoption model to today's emerging technologies, like digital twins and exploring the perception of Transmission System Operators and Distribution System Operators, when it comes to the adoption of digital twins in the Dutch energy sector. This work is to the best of my knowledge original except where acknowledgement and references are made to previous scientific work.

Lastly, but most importantly, I would like to acknowledge my indebtedness and render my warmest thanks to the graduation committee members and company supervisors without whose guidance this research would not have been possible. Thanks to prof. Ben Wagner for his patience, encouragement and invaluable recommendations throughout all stages of the thesis work. In addition, I express my sincere gratitude to prof. Frances Brazier for her constructive feedback, extended discussions and valuable suggestions which have contributed greatly to the improvement of the thesis. Moreover, my sincere thanks go to prof. Yilin Huang for her tips and advise to ensure that I stayed on track and the quality of research work was up to the mark as per expectations.

Furthermore, I convey my appreciation to Walter De Leeuw and Martin van den Ing for their constant support on all aspects of the thesis work right from the start up to the end be it on the scientific front or practical aspects. Also special thanks to the team at BearingPoint in particular, David Bergsma, Henk Groeneveld, Michiel Musterd, Lucas van Luijtelaar, Michael van der Wielen and Annelieke Hoenderkamp, for their support, guidance and help arranging interviews with the energy market participants in the Netherlands.

Abhinav Durani
Delft, August 2021

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INTRODUCTION

This is the introductory chapter of the thesis which begins by narrating the background of the research through describing the context of digital twins in the energy sector. Following the background, the author delineates the problem definition by explaining the knowledge gap that the research aims to fill, the objective(s) and scope of the research and the research questions that were formulated to achieve these objectives. This chapter ends by reporting the research methodology adopted by the author and the structure (outline) of the thesis.

The research method primarily adopted in this chapter is: **Desk research** of secondary data sources of both academic and non-academic in nature

1.1. BACKGROUND

Back in 2018, the World Economic Forum (WEF), observed that the top 20% of companies by productivity within any given industry are investing in new technologies to further accelerate revenue growth and productivity. WEF forecasted that the total new digital technology investments from 2016 to 2020 are expected to increase by 13% at a compound annual growth rate to $2.4 trillion per year (WEF, 2018). These investments are made with the intention to drive new efficiencies, enhanced customer experiences and new business models, in the hope of higher revenue growth. The return on these digital investments (in terms of productivity) varies across industries - however, industry leaders consistently achieve a greater productivity increase than industry followers regardless of the industry in question (WEF, 2018). One such emerging technology that has been in the limelight are Digital Twins. Along the same lines, investments in digital twins are expected to reach $12.7 billion (€11.3 billion) by 2021; an increase of 17% from $10.8 billion (€9.6 billion) in 2019 (Juniper Research, 2020).

The conceptualization of digital twins was presented by Michael Grieves from the University of Michigan in 2002. However, Grieves did not call it 'Digital Twin' as it is known as today - he introduced it as a model for Product Lifecycle Management (PLM) without giving a name (Grieves, 2002). The term 'Digital Twin' refers to a comprehensive physical and functional description of a component, product or system, which includes all the relevant information useful in all the lifecycle phases of an asset (Hehenberger & Bradley, 2016). In simpler words, a digital twin is a digital up-to-date replica of an actual physical asset. Such a digital representation of a physical asset can help determine the lifecycle stage of an asset, evaluate current operating conditions, predict future behavior and optimize machine up-time by preventing untimely asset breakdowns.

On the other hand, emerging trends and developments such as: energy transition and shifting consumer electricity demands has caused energy networks across the world to become more complex to control, optimize and regulate. Losses from the transmission and distribution of electricity due to inefficient (components) networks leads to generating a higher electricity supply to meet the same level of demand. On top of which unexpected breakdowns, power outages and power-grid overload can not only reduce operational efficiency of the network, but, also lead to impairments of crucial parts of the network. In contrast, a digital twin, promises to proactively manage the available capacity on the network and optimize the efficiency of its component-assets. Furthermore, the substantial monetary expenditures on the Digital Twin Technology calls for a probe into the strategic considerations that organizations must take into account with the utilisation of a digital twin and the critical success factors that are vital for implementing such twins. The fact that industry leaders achieve greater productivity-growth relative industry followers with investments in digital technologies, begs to explore the market conditions/strategies adopted by these firms that differentiate them in their adoption of digital twins to the operational ecosystem.

1.2. PROBLEM DEFINITION

In this section, the author describes the knowledge gap that this research aims to fill, the scope and objectives of the research and finally, the research questions and methodology adopted to achieve the research objectives.

1.2.1. KNOWLEDGE GAP

The knowledge gap that this research aims to fulfill is two-folded: firstly, the thesis applies a technology adoption model to digital twins and secondly, it aims to establish an understanding of the current perceptions of digital twins in the Dutch Energy sector. The existing literature on technology adoption models is vast and some of the adoption models have been applied to several emerging technologies in the past; however, as per the knowledge of the author, none of the existing literature, currently, apply technology adoption models to digital twins. This thesis aims to fill-in this knowledge gap by identifying the most fitting technology adoption model and applying it to digital twins by the means of identifying the most relevant adoption variables. Secondly, existing scientific literature does describe the perception of digital twins in terms of their risks, benefits and potential use-cases among other factors; however, there is limited depiction, at present, when it comes to the notion of digital twins in the context of the Energy sector, more so in the Netherlands. Since, the adoption of digital twins is still in its infancy especially in the Energy sector, this research aims to explore the current opinions around digital twins in the Dutch Energy sector.

1.2.2. RESEARCH OBJECTIVE & SCOPE

Research Objective: The objective of this research is three-fold. First, to identify the variables that are relevant when it comes to the adoption of innovative technologies such as digital twins. Second, to develop/apply organizational technology adoption models to digital twin adoption. Third, more importantly are the exploratory aspects of the research i.e., to gather insights from participants in the Dutch energy sector around the adoption of digital twins in terms of benefits, risks, perceptions and motivation among others. In essence, the intent is to compare and contrast the differences and similarities in these insights between various energy market participants of differing organizational characteristics.

Scope: The scope of this research is limited to the adoption of digital twins in the Dutch energy sector and predominantly focuses on Transmission System Operators (TSOs) and Distribution System Operators (DSOs). Investigating the technicalities of digital twins (e.g.: software architectures) lies outside the bounds of this research.

1.2.3. RESEARCH QUESTIONS & METHODOLOGY

In order to achieve the objective of this research and fill-in the knowledge gap, one central research question has been devised which has been divided further into 4 sub-research questions.

Central RQ*: How can digital twin adoption by grid operators in the Netherlands be explained by a technology adoption model?*

- ***Sub-RQ-1****: Which existing technology adoption framework(s) is the most fitting when it comes digital twin adoption?*

  The aim of this research question is to study several technology adoption models and identify the most appropriate adoption model for digital twins. Like the previous questions, the main research method adopted to answer this question is also secondary desk research.

- ***Sub-RQ-2****: Which variables are relevant in the adoption of digital twins by grid operators?*

  The objective of this research question is to determine the factors that are relevant when it comes to the adoption of digital twins by Dutch TSO/DSOs. The author will conduct desk research of secondary sources of literature such as: scientific papers, academic articles, books and conference proceedings.

- ***Sub-RQ-3****: What are the perceptions of Dutch grid operators when it comes to digital twins and how do they differ with TSO/DSO characteristics (such as: organizational size, net profit, circuit length)?*

  This research question is aimed to contrast and compare the perceptions of digital twins as experienced by Dutch TSO/DSOs of varying characteristics. The primary research method used to answer this question are (semi-structured) interviews.

- ***Sub-RQ-4****: What is the relationship between TSO/DSO characteristics (such as: organizational size, net profit, circuit length) and organizational absorptive capacity?*

  By the means of the above research question, we aim to identify a relationship between organizational absorptive capacity and TSO/DSO characteristics such as: organizational size, net profit, circuit length. The primary research method used to answer this question are targeted questionnaires which were sent to technology adoption decision-makers following the (semi-structured) interviews.

As shown in figure-1.1, in order to answer the above research questions and in turn, achieve the research objective, a research methodology that triangulates three techniques: desk research, (semi-structured) interviews and targeted questionnaires was adopted.

1.3. THESIS OUTLINE

The structure of the thesis goes along similar lines as they research methodology. In this chapter, the foundation i.e. introduced the concept of digital twins, the context of the energy sector, the knowledge gap that the research aims to fill-in and more importantly, the research questions that we expect to answer thorough the course of the thesis, has already been laid down. The next chapter dives deeper into the past literature studies and describe the concept of digital twins and the tends in the energy sector in detail. We will also compare and contrast technology adoption models and evaluate which one would best-fit the case of digital twins. The third chapter, looks into the relevant technology adoption variables existing in the past literature, scientific articles and academic work at depth from three perspectives: Technology-based variables, Organization-based variables and External variables. After having investigated the adoption variables, the variables of interest for this thesis are narrowed by the means of a selection & exclusion criteria. Chapter-4 describes the model validation process and the methods through which the selected variables are further investigated: (semi-structured) interviews and

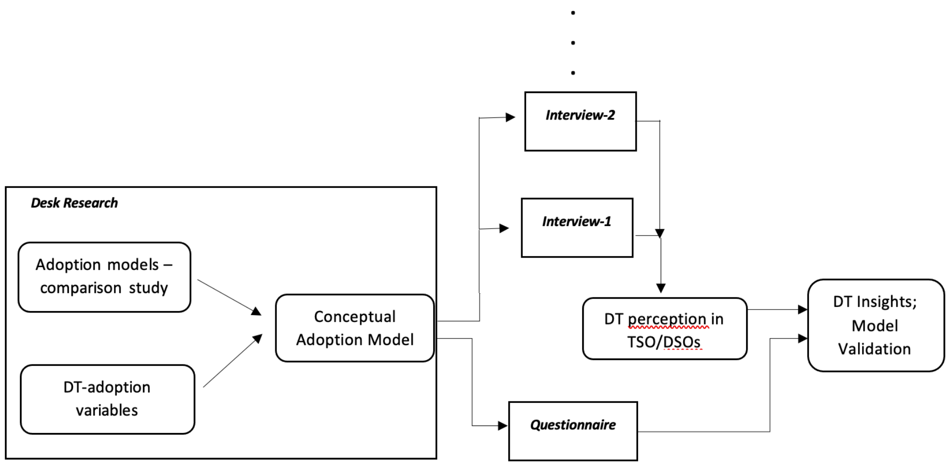

Figure 1.1: Research Methodology

targeted questionnaires. Chapter-5 begins by discussing the findings from the interviews and the targeted questionnaire. As mentioned earlier, the interviews are meant to build an understanding of the (current) perception of digital twin amongst Dutch TSO/DSOs and the targeted questionnaires are meant to establish a relationship between TSO/DSO characteristics and organizational absorptive capacity. Lastly, chapter-6 concludes the thesis by presenting the (summarized) findings and limitations of the research. This chapter also includes the author's reflection on the thesis work from three perspectives: Academic, Societal/Managerial and Personal. The appendix, at the end of the thesis, contains interview transcripts which have been completely anonymized to meet the guidelines/arrangements discussed in the data management process keeping in mind the privacy of the interviewees.

2

Literature Review

This chapter begins with a brief summary of the concept and critique of digital twins. Then, the author describes the current shift to digitalization in the energy sector; followed by the potential of digital twins in the energy sector. The chapter concludes by examining the existing literature around technology adoption model to identify the model/framework that is the most fitting in the context of digital twin adoption.

The research method primarily adopted in this chapter is: **Desk research** of secondary data sources of academic nature

2.1. DIGITAL TWIN - CONCEPT & CRITIQUE

In this section, the author describes the concept of digital twins in detail, the various types of digital twins as per the literature and then moves onto explaining the misconceptions (critique) around them.

2.1.1. DIFFERENCES IN SCHOOLS OF THOUGHT

A digital twin is a digital replica of a physical asset, however, in literature there is no common understanding concerning this term. It is used slightly different over the disparate disciplines (Kritzinger et al., 2018). The idea of digital twin was presented by Michael Grieves in 2002 as the Product Lifecycle Management (PLM) without giving a name. It was later named the Mirrored Spaces Model (MSM) and then the Information Mirroring Model. The model was finally renamed as the Digital Twin by a NASA scientists John Vickers (Grieves, 2002). Regardless of the change in name, the underlying concept of the digital twin has remained the same, whilst only differing applications. On the other hand, different schools of thought (scientists) have had different interpretations of the concept of digital twin mostly based on the context and/or application environment in question. Glaessgen and Stargel interpret a digital twin as an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system that utilises available physical models, sensor updates and fleet history to mirror the life of its corresponding flying twin (Glaessgen & Stargel, 2012). In other words, Glaessgen and Stargel define digital twins in the context of the aircraft industry, where conventional simulation techniques are deemed to be insufficient for the assessing the impact of dynamic externalities on the components of an aircraft such as: airframe, propulsion and energy storage. For instance, the behavior of these components under higher loads and more extreme service conditions over longer time periods is simply impossible to simulate.
In the service management industry, Bolton and his colleagues decipher a digital twin as a dynamic virtual representation of a physical object across its lifecycle, using real-time data to enable understanding, learning and reasoning (Bolton et al., 2018). It is noticed from the definition here that, the underlying idea is the same, but, the focal application is to deliver better customer experience through real-time data.

Similarly, Soderberg and colleagues in their work describe digital twin as a simulation and seamless transfer of data from one lifecycle phase to the other (Söderberg et al., 2017). Their work focuses on the optimization of the conventional geometric assurance process: design phase, pre-production and production phase by the use of digital twins in every phase. This interpretation of digital twins, showcases the potential of digital twins in the manufacturing industry, where traditionally, simulations are mostly in conducted in the design phase with estimated or historical data as the input.
El Saddik takes the concept of digital twins one-step further - most application areas of digital twins prior to his work were, to a certain extent, focused on increasing operational efficiency be it: a manufacturing process or a product's lifecycle. His work re-defines digital twins as digital replications of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds (El Saddik, 2018). In other words, Digital twins can also be made of living entities (i.e. humans) which enables the analysis of physical, physiological and contextual data to improve quality of life and enhance well-being. For instance, by the use of a digital twin, a heart attack can

be predicted before it actually occurs and preventive steps are taken.

Digital twins have been interpreted across a diverse range of applications in various industries with the likes of aerospace, customer experience, production management and manufacturing as seen above. However, the adaptable definition of a digital twin in the energy industry was not found, this can already be regarded to an initial knowledge gap in the industry and to the fact that use-cases specifically catering this sector are slowly, but, surely developing.

2.1.2. TYPES & MISCONCEPTIONS

A digital twin has a few fundamental attributes regardless of the application, industry or use-case in question. Based on the lifecycle stage of the physical asset, a digital twin can classified into three types (Grieves, 2019):

- **Digital Twin Prototype (DTP):** A DTP exists prior to the existence of the physical asset, with the aim to analyze all the possible design variants to develop a physical product

- **Digital Twin Instance (DTI):** DTI is the Digital Twin of each individual produced artifact after it is manufactured. For instance, one can think of a wind turbine in particular harsh environment setting as the DTI. DTPs exist for all complex component parts, whereas DTIs exist only for components, where it is essential to know the behavior/performance/operation of a product through its entire lifecycle.

- **Digital Twin Aggregate (DTA):** DTA is the collection of instance (DTIs) whose data is used to interrogate/control the physical product and its prognostics. DTAs are both longitudinal and latitudinal representation of behavior of the asset. The longitudinal value comes from the fact that DTAs correlate state (input) changes with subsequent outcomes. And, the latitudinal value arises when a small group of DTIs learn from actions of the asset (Grieves, 2019).

Furthermore, as shown in figure-2.1, (Grieves, 2002) suggests that regardless of their type, digital twins adopt a single-mode model i.e., his research advocates that Digital Twin and Physical Twin (Physical object) reside in two distinct spaces and the data/information flow between the two happens once at a time and not concurrently.

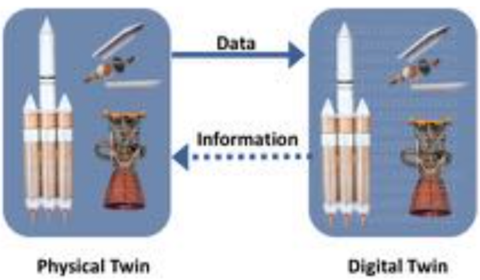

Figure 2.1: Single-Mode of working DT model (Grieves, 2002)

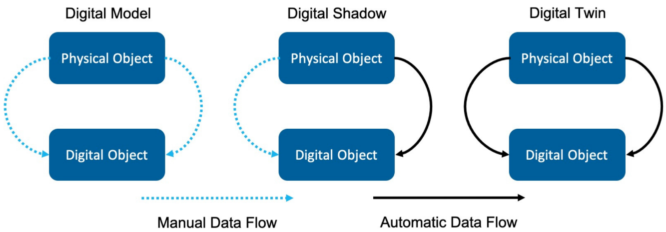

Figure 2.2: Clarifying misconceptions of Digital Twins (Fuller et al., 2020)

However, this assumption is rather simplistic in practice, due to the fact that there are several use-cases of digital twins using mixed methods of working (i.e. simultaneous two-way communication between physical asset and digital twin) by capitalizing upon complementary technologies such as AI, IoT and advanced analytics. [1]

Another common misconception of digital twins at present, is that they are the same as simulations that already exist and are nothing more than a 'marketing term'. Prior to the creation of the so-called 'Digital Twins', there existed several engineering software, simulations and digitalized models which analyzed massive data-sets of different physical components. However, this lead to, data-sets of a given physical asset being isolated from each other, leading to low efficiency and low utilization of these valuable data (Liu et al., 2020). A common misconception with the term 'digital twins' is that the term is synonymous to complex simulations. Some believe digital twins have to be an exact 'one-to-one' 3D model of a physical asset and others individuals that think they are no different from existing 3D models. As depicted in figure-2.2, Fuller et. al defines three concepts that helps identify (and clarify) most misconceptions around defining digital twins as per the literature. A **digital model** is described as a digital version of a pre-existing physical asset and there is no automatic data exchange between the physical model and digital model. This implies after the digital model is created a change made to the physical object has no (automatic) impact on the digital model (put simply, these are 'existing' 3D simulation models) Some examples of digital models include: product designs/drawings (Fuller et al., 2020). Secondly, he defines **digital shadows** as a digital representation of an object that has a one-way information flow between the physical and digital object and the change in the state of the physical object leads to a change in the digital object but not vice versa (Fuller et al., 2020). Finally, a **digital twin** is when the data flow is fully integrated bidirectionally between the physical object and the digital object. A change made to the physical object automatically leads to a change in the digital representation and vice versa (Fuller et al., 2020).

Hence, digital twins are much more than only simulations based on theoretical and static models. With the development of enabling technologies such as the Internet-of-Things and Big Data, digital twins offer a comprehensive solution allowing for data storage, simulations in a real-time dynamic environment and the possibility to manage and control the physical asset via the digital twin itself. On the other hand, given the

[1] Example: Microsoft Process Twin - https://info.microsoft.com/rs/157-GQE-382/images/Digital%20Twin%20Vision.pdf

data-driven nature of digital twins, this technology also faces ethical roadblocks when it comes to data management, privacy and security (Rasheed et al., 2019). As the enabling technologies of digital twins are still developing themselves, digital twins face technological challenges including but not limited to: real-time data communication (latency), interaction with the physical asset and the real-time simulations themselves can require a large scale infrastructure and computation power. Given the size and nature of these challenges, organizations may prefer to use bifurcated simulation techniques as before, rather than transitioning to a one-stop data shop that comes with a (new) range of threats to data protection.

2.2. THE SHIFT TOWARDS DIGITALIZATION

All areas of our economies are leveraging upon the potential provided by Information and Communications Technology (ICT) services, this includes, recently, the energy sector. So far, one of the most significant impacts of digitalization in this industry has been on the level of energy consumption. Digitalization has led to increased energy consumption (Lange et al., 2020). His work is summarized by categorizing the influence of digitalization on energy consumption into four effects:

- **Direct effects:** The ICT sector's energy has experienced strong increases of (technical) energy efficiency, but, has also developed from the production, usage and disposal ICT services itself.
- **Efficiency and rebound effects:** Digitalization allows for more efficient production of electricity, however, this can lead to more energy-intensive behavior, if not regulated.
- **Economic growth:** Labor and capital productivity increases from the digitalization of energy, in turn, leading to economic growth.
- **Sectoral change:** The growth of ICT services does not replace the existing energy networks, but, but comes on top of the existing production.

In other words, his work points out a positive correlation between digitalization and energy consumption i.e. more levels of digitalization leads to higher levels of energy consumption. To factorise this correlation, (Lange et al., 2020) derives a mathematical expression for change in energy consumption due to digitalization given as follows:

$$\hat{E} = \hat{E}_{\mathrm{ICT}} * \pi_{\mathrm{ICT}} + \pi_{\mathrm{R}} * \hat{Y} + \hat{a} * \pi_{\mathrm{R}} + \sum_{i=1}^{n-1} \hat{s}_{\mathrm{i}} * \pi_{\mathrm{i}} \tag{2.1}$$

In the above equation, the impact of digitalization on the change in energy consumption $\hat{E}$ is attributed to: change in ICT sector's energy consumption itself ($\hat{E}_{ICT}$); change in in economic growth ($\hat{Y}$); change in energy efficiency, in turn, change in energy intensity ($\hat{a}$); and, Sectoral change ($\hat{s}_i$). Therefore, overall, it is argued that digitalization tends to increase energy consumption in most areas of the economies including the energy sector. For specifically, the energy sector, this means that the digitalization of electricity systems ought to improve reliability and reduce operating costs. Since, digitalization

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correlates to a higher energy consumption, electricity must be generated at lower costs and greater reliability of the energy network in order to match the higher electricity demand and still remain profitable. On the contrary from an environmental perspective, a critique to the above correlation is that: if greater levels of digitalization lead to increased energy consumption, then, considering the impact of higher consumption on climate change, it would not be feasible to digitalize the energy sector even further, if the (digitalized) components of the network are left unregulated.
From an organizational perspective, digitalization of the energy sector has also led to development of new business models in-and-around the adoption of digitalization. In the context of energy trading within micro-grids, several business models have been developed based on the ownership of the underlying physical assets (such as: grid & generators) and operational responsibility (Di Silvestre et al., 2018). He describes four emerging business models as a result of digitalization in the energy sector:- Single user model, DSO with unbundling exemption model, Hybrid model and Third-party model. Hence, depending on the existing environment and the asset ownership structure at the TSO/DSO, the business model deployed would vary from other TSO/DSOs even in the same geographical location. Therefore, it becomes even more challenging for TSO/DSOs contemplating the use of digital twin technology to scrutinize the success determinants based of the business models used in the past.

2.3. THE POTENTIAL OF DIGITAL NETWORK TWINS

For convenience sake, when we refer to digital (network) twins, the context of using digital twins in companies within the energy sector is implied; the terms digital (network) twins and digital twins are used invariably. (Zhou et al., 2019) envisions the potential of Digital (Network) Twins as multi-layer interaction between IT applications and the digital twin each addressing different sub-components of the physical power grid to manage the its operations in real-time as illustrated in figure-2.3.

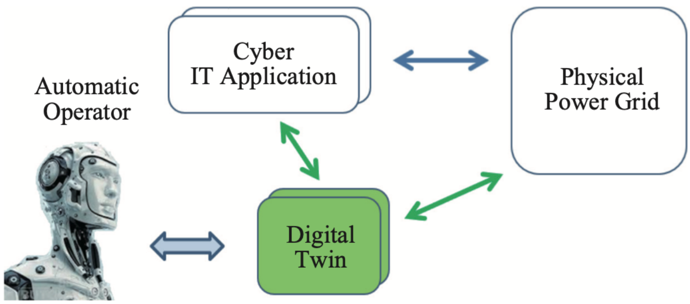

Figure 2.3: Illustration of potential DT-based automated grid operator (Zhou et al., 2019)

The above illustration is one of the instances of the full-scale potential of Digital (Network) twins (i.e. automated grid operation) in the energy sector. However, this is a full-fledged use-case, in which grid operation, optimization, utility asset management, fault-prediction and control all take place via the digital twin. In other words, the operator has to only make modifications in the digital twin - based on the input and the operating conditions, the twin will communicate the command to the physical asset and act as requested. The next level of automation of this concept would be the merger of machine learning techniques with the digital (network) twin, allowing the twin to learn from its historical data (i.e. unsupervised) and its mistakes (i.e. reinforcement) to predict (or perform) real-time grid commands to the physical asset without the need of an operator (Maheshwari et al., 2020). Given the potential of digital twins, it ought to be realistic to expect proactive power capacity management on an electrical network. Furthermore, the work of (Maheshwari et al., 2020) suggests that data-insights provided by the twin are utilized to maximize the allocative efficiency of assets on the network - process innovation, in a certain sense. The architecture of digital (network) twins combines raw data, dynamic simulation techniques and analytics, enabling a wide-range of applications and/or benefits for companies within the energy sector.

2.4. ORGANIZATIONAL TECHNOLOGY ADOPTION THEORIES

The organizational technology adoption theories that are the focus of our research revolve around the decision-making process, i.e., theoretical frameworks that organization use to determine whether an investment in a certain technology is sensible or not. Scientific theories pertaining to the next stage (i.e. after the decision to invest in a technology is made) of technology governance do not lie within the scope of the research given the fact that our primary focus is the decision-making process itself rather than technology governance.

2.4.1. TECHNOLOGY-ORGANIZATION-ENVIRONMENT FRAMEWORK

Tornatzky and Fleischer's Technology-Organization-Environment (TOE) theory is one such organizational-level framework that classifies a firm's technology adoption decision into three contextual factors: Technological Context, Organizational Context and Environmental Context (Dwivedi et al., 2012).

As described in figure 2.4, the technological context not only includes technologies that are already deployed at the firm, but, also those that are available in the market but not currently in use. Based on the characteristics of the technology in consideration and the firm's existing technology base, the new technology can either be competence-enhancing or competence-destroying. Competence-enhancing technologies enable firms to gradually improve their expertise by building upon existing technologies, whereas, competence-destroying technologies render existing technologies of the firm as obsolete (Dwivedi et al., 2012). Therefore, from a technology perspective the theory stipulates that firms must consider whether the new technology complements their existing portfolio of technologies or it completely reshapes the way of working, prior to making the decision to invest in the new technology. Secondly, the organizational context includes but is not limited to the formal/informal linking structures between employees and/or teams, inter-and-intra organizational communication processes, size of the organization and the amount of slack resources (Dwivedi et al., 2012). Organizational structures that foster and promote innovation (such as: organic and decentralized structure) can have a bias towards adopting new technologies even if they foresee minor to limited benefits of adoption. Lastly, as per Tornatzky and Fleischer's theory, the external task en-

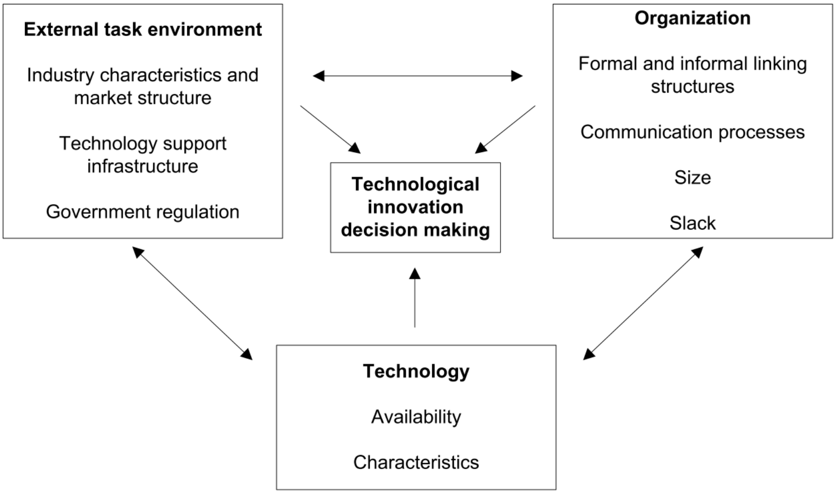

Figure 2.4: Technology-Organization-Environment (TOE) Framework

vironment context includes the industry structure, the presence/absence of technology support infrastructure, and the regulatory environment. Hence, a firm must examine a technology investment decision from the lens of the technology itself, the organizational variables and the external environment that the firm operates in.

2.4.2. TECHNOLOGY ADOPTION DECISION MODEL

In the application of digital libraries, Oguz in his research identified several organizational-level influences that take place in a technology adoption process such as: organizational structure, management style, focus and direction of and external relationships (Oguz, 2016). Figure 2.5, depicts that Oguz classifies the decision of adopting technologies to be influenced by two factors: Internal and External Inputs. Internal inputs consist of the structure of the organization, the leadership style of the higher management and the existing focus & direction that the organization is heading towards and aims to achieve. On the other hand, external inputs include external relationships that a firm's employees build, for instance, with professional associations, suppliers, distributors and customers. As per this theory, the technology adoption decision depends upon the inputs from these external relationships and inputs from the internal management characteristics of the organization.

His research argues that flexible form of organizational structures promoted an environment where contributions from relevant stakeholders allowed for technology-related decisions to be made collectively. Furthermore, information for technology decision flowed from bottom to upper ranks in the organization, whereas, the actual decision making and its implementation was a top-down process. In contrast to the TOE theory, it is noticed here that, this framework does not evaluate the characteristics of the technology itself.

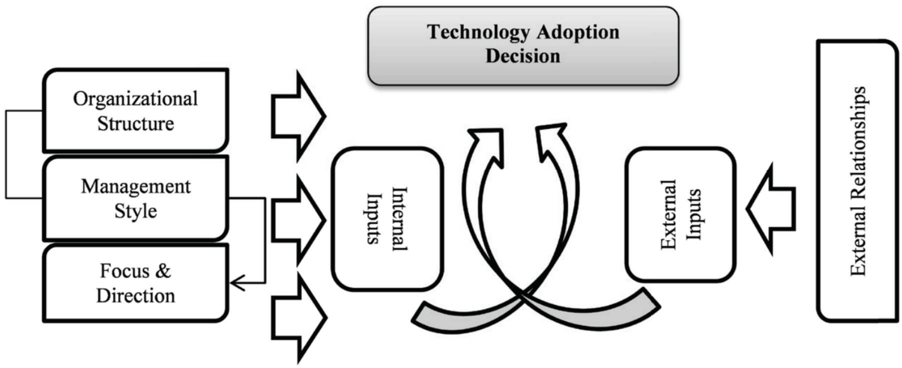

Figure 2.5: Technology Adoption Decision Model (Oguz, 2016)

2.4.3. OTHER THEORETICAL APPROACHES

There are several other theoretical frameworks such as the Technology Acceptance Model (TAM), Motivational Model (MM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), however, most of these theories have units of analysis at an individual level and not at the organizational level.

2.4.4. COMPARISON STUDY

As depicted in figure-2.6, there have been several adoption models developed in the past that explain the acceptance of a given technology. In the context of digital twins, many of the criterion to select an adoption model stem from the characteristics of an emerging technology. Halaweh in his research points to several characteristics of emerging technologies (ET) the likes of digital twins such as: ET Uncertainty, ET network effects, ET costs, Unobvious impact, limited availability and limited know-how/research (Halaweh, 2013). According to his research, uncertainties of emerging technologies can take various forms included but not limited to: (Un)obvious social/ethical impacts, uncertainty in costs due to the novelty of technology, unpredictability in industry standards, business models and pricing among others. These features are mapped into five categories: Technological Characteristics, Adopter's demographics, Adopter's perception, Organizational factors and External Factors. Technological characteristics include factors that have anything to do with the technology itself (e.g.: availability). Adopter's demographics refer to factors such as: age, level of education, gender, etc. of the adopter (decision-maker, i.e., the person who makes the decision to implement a technology in his organization by virtue of his role or knowledge) in the organization. Similarly, adopter's perception includes factors such as: the beliefs, perceived risks/benefits and motivation of the decision-maker to be for or against the technology. Organizational factors pertains to things like resources, capital, knowledge among other factors. Finally, external factors include looking at industry standards, business models, regulations and associated impacts. Furthermore, as the objective of the research is to look into the adoption of digital twins within TSO/DSOs (organizations) of the Energy sector in the Netherlands; another criteria relevant for the adoption model is that the level of observation of the

	Technological Characteristics	Adopter's demographics	Adopter's perception	Organizational factors	External factors	Firm level?
TRA *(Fishbein and Ajzen, 1975)*	No	No	Yes Beliefs; Motivation; Norms; Behaviour	No	No	No
TPB *(Ajzen, 1991)*	No	No	Yes Beliefs; Attitude, Norms; Behaviour; Intentions	No	No	No
TAM *(Davis, 1989)*	No	No	Yes Attitude; Perceived Usefulness; Perceived Ease of Use	No	No	No
TAM Extensions *(Wixom and Todd, 2005)*	No	Yes Demographics; Personality	Yes Attitude; Perceived Usefulness; Perceived Ease of Use	No	Yes System Characteristics	No
DOI *(Rogers, 1995)*	No	No	Yes Attitude towards Change;	Yes Size; Slack; Complexity	Yes System Openness	Yes
UTAUT *(Venkatesh et al., 2003)*	No	Yes Gender; Age; Experience	Yes Performance Expectancy; Effort Expectancy	Partly Social Influence;	Yes Extrinsic Motivation; System Characteristics	No
TOE *(Tornatzky and Fleischer 1990)*	Yes Tech characteristics; Availability	No	No	Yes Size; Slack; Resources	Yes Regulation; Market structure	Yes
Lacovou et al. model *(1995)*	No	No	Yes Perceived benefits;	Yes Org readiness; Resources IT/Financial;	Yes External pressure; Trading partner power;	Yes

Figure 2.6: Technology Adoption Models - Compared

model should be at the firm level and not only at the level of individual employees.
The adoption models: Theory of Reasoned Action (TRA) and Theory of Planned Behaviour (TPB) are focused around an individual's behavior when it comes to adoption of technology. According to TRA, an individual's intentions determine his or her actual behavior. Intentions are in turn determined by the individual's attitude toward this behavior and subjective norms with regard to the performance of this behavior (Fishbein & Ajzen, 1975). TRA has been formulated to predict an individual's behavior only in a real voluntary situation, not in a mandatory context. TPB extends TRA to consider the mandatory situations by adding a new construct: perceived behavior control (Ajzen, 1991). He defines this construct as the perceived ease or difficulty of performing a certain behavior (Ajzen, 1991). Both TRA and TPB have been widely applied in the past to comprehend individual (user) technology acceptance.
On the other hand, the Technology Acceptance Model (TAM) is centered around two individual beliefs of using technology: perceived usefulness and perceived ease of use. Perceived usefulness is described as the extent to which an individual believes that using a particular technology would enhance his/her job performance (Davis, 1989a). Perceived ease of use is the degree to which an individual believes that using a particular technology would be free of effort (Davis, 1989b). Davis found that perceived usefulness is the strongest predictor of an individual's intention to use an technology (Li, 2010). Furthermore, TAM is widely regarded as the most influential theory in information systems adoption. Several researchers have also extended TAM by introducing factors such as: subjective norm, perceived behavioral control, and self-efficacy ((Hartwick & Barki, 1994); (Mathieson, 1991); (Taylor & Todd, 1995)). Others include additional factors from the diffusion of innovation (DOI) theory, such as trialability, visibility, or result demonstrability ((Agarwal & Prasad, 1997); (Karahanna & Straub, 1999); (Plouffe et al., 2001)). The most prominent extension of TAM has been the introduction of external variables or moderating factors to the two major belief constructs (perceived usefulness and perceived ease of use), such as personality traits and demographic characteristics ((Gefen & Straub, 1997); (Venkatesh et al., 2000)). In addition, the Unified Theory of Acceptance and Use of Technology (UTAUT) proposed that there are three constructs which are the main determinants of intention to use a given technology; performance expectancy: user expectations that using the given technology will help him/her improve work performance; effort expectancy: the extent of ease linked to the use of the technology; and social influence: the degree to which a user perceives that others believe that he/she should use the new technology (Venkatesh et al., 2003). Despite these extensions, TAM still does not account for the characteristics of the technology itself and the unit of observation of adoption remains the individual.
Diffusion of Innovations (DOI), Technology-Organization-Environment (TOE) framework and Iacovou model are the only ones that analyze technology adoption at the firm level, whereas, the others: TRA, TPB, TAM (and its extensions) and UTAUT look at the individual level (Oliveira et al., 2011). Based on the DOI theory, organizational innovativeness (extent to which a firm adopts new technology) is dependent on three variables: Individual (leader) characteristics (e.g.: attitude towards change), internal organizational structural characteristics (e.g.: formalization of processes, size, resources), and external characteristics of the organization (system openness) (Rogers, 1995). On the other hand,

Iacovou et al.'s adoption model is based on three factors: perceived benefits, organizational readiness, and external pressure (Iacovou et al., 1995). Although both these models analyze the adoption at a firm level, they have limited to no considerations about the nature of the technology itself. Given digital twins are emerging technologies in their infancy, looking at the technological perspective is also an essential factor when it comes to their adoption. A note to keep in mind is that the TOE framework has undergone limited theoretical (academic) development since its conceptualization, like many other adoption models (Baker, 2012). However, compared to other technology adoption models, the TOE framework is more comprehensive as it remains broad and allows for a higher degree of freedom to include other factors, variables and measures of adoption depending on the context, in turn, there is no significant need to rework the theoretical model itself (Zhu & Kraemer, 2005). Hence, in the context of our research, the TOE framework was used as the central model of adoption and to combat its weaknesses (as shown in figure-2.4.4, certain aspects of TAM extensions were also included. More specifically, individual adopter characteristics such as: demographics and attitude; and perceptions of the technology have been included in our TOE framework.

2.5. CONCLUSION

This chapter examined the concept of digital twins by diving into the different schools of thought present in the existing literature. In broad terms, a digital twin is defined as a virtual representation of any physical asset/object. However, in academic literature there is no common definition around what a digital twin ought to exactly entail - the term has been used (defined) slightly different across various disciplines, applications and industries. Next, the chapter described the types of digital twins and explained the common misconceptions around digital twins. Followed by which, the author portrayed digital twins in the specific context of the energy sector by inspecting the shift towards digitalization and the potential of digital twins for grid operators. Lastly, the author concluded this chapter by investigating technology adoption models and identified the TOE framework as the most-fitting model when it comes to digital twin adoption.

3

ADAPTING THEORETICAL ADOPTION MODEL

There are several variables at play, when it comes to digital twin adoption in the context of the Dutch energy sector. As described in the last chapter, the author applies the TOE framework and classifies digital twin adoption variables into three groups of variables: Technology-based, Organization-based and External. In this chapter, each category is investigated in detail leading to the following variables: Complexity, Compatibility, Perception, Technological Characteristics, Availability, Organizational culture, Organizational size, Budget size, Incentives, Management support, Absorptive capacity, (decision-maker's) Demographics, Attitude towards technology, Regulations, Competitive pressure and Network effects.

The research method primarily adopted in this chapter is: **Desk research** of secondary data sources of both academic and non-academic in nature

3.1. Technology-based variables

In this section, we investigate technological variables that are relevant for the adoption of digital twins in the energy sector. The relevant technology-based variables include: Complexity, Compatibility, Perception, Technological Characteristics and Availability.

3.1.1. Complexity

The notion of complexity has been defined diversely by different authors in several disciplines. Some analyse complexity in terms of dynamic or static levels (Kaur et al., 2009), others look at it from a system versus component perspective (Schneberger & McLean, 2003). Complexity of technology has many different dimensions and must be considered on a contextual basis (Blohmke, 2014). We use the definition of technological complexity as experienced by organizations based on the research of Wang and Tunzelmann. Complexity in organizations is assessed in terms of the dimensions of 'depth' and 'breadth'. Complexity in 'depth' refers to the novelty and sophistication of a subject, whereas complexity in 'breadth' refers to the range of areas that has to be investigated to develop a particular subject (Wang & Von Tunzelmann, 2000). In our context, complexity in 'depth' implies the level of newness (or unfamiliarity) of digital twins within a TSO/DSO and 'breadth' would imply the degree of steps/attributes TSO/DSOs must looking into, prior to making the decision to adopt digital twins. In other words, if a TSO/DSOs has had fairly limited interaction with digitalization projects in the past, then the perceived complexity of digital twins within the organization in terms of depth is expected to be high. Several empirical studies in the past suggest that technology complexity is negatively correlated to organizational technology adoption (Al-Gahtani et. al, 2014; Aizstrauta et. al, 2014; Chin et. al, 2015).

3.1.2. Compatibility

Compatibility is the defined as the extent to which a new technology/innovation is considered to be in line with an organization's incumbent technology, existing processes, experiences and values (Rogers, 1995). The conventional view of compatibility as described by Rogers is that, technologies that are incompatible with an organization's existing culture and way of working are hindered in their adoption relative to compatible technologies. The hindrance in the adoption of technologies that are perceived as incompatible in an organization stems from the fact that these 'new' incompatible technologies bring many uncertainties with them (e.g.: new procedures, tasks, culture, etc.) which employees may not always be willing to accept. Furthermore, technology adoption theories in the past have classified compatibility into two types: Practical compatibility and Value Compatibility. The former refers to the compatibility of the new technology with the incumbent technology in terms of technical characteristics and feasibility of implementation (Klein & Speer, 1996). Value compatibility, on the other hand, is associated to the cultural fit of the new innovation with the target user's/organization's value and expectations.

In later studies, Karahana et. al describe four constructs of compatibility: i) Compatibility with preferred work style, ii) Compatibility with existing work practices, iii) Compatibility with prior experiences and iv) Compatibility with values (Karahanna et al., 2006). As the name suggests, the first three constructs are associated with Practi-

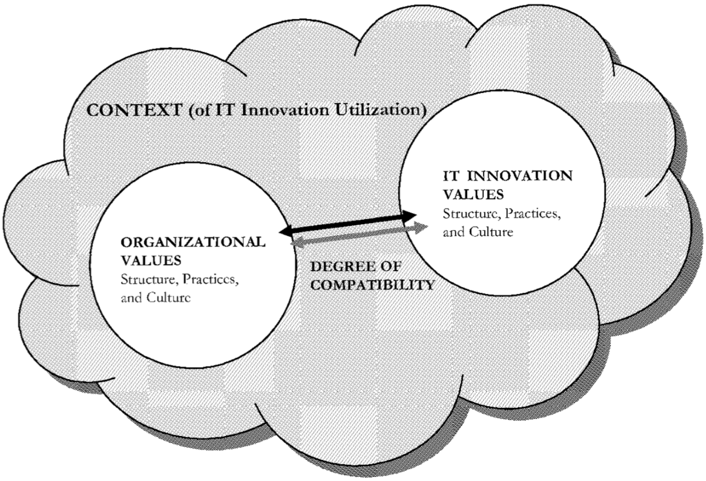

Figure 3.1: Value Compatibility in Technology Adoption (Bunker et al., 2006)

cal compatibility and the later with Value compatibility. In addition, assessing practical compatibility is relatively straight-forward: either a technology is an extension of the existing technical procedures and work styles or it is a breakthrough innovation which changes the existing way of working. On the other hand, measuring value compatibility is more challenging due to the abstract nature of values in an organization. As shown in figure-3.1, Bunker et. al recommends organizations to consider the degree of compatibility of a new technology at three levels: (Organizational) Structure, Practices and Culture (Bunker et al., 2006). The higher the degree of compatibility at these three levels, the more is the value compatibility of the technology from an organizational perspective. As shown in figure-3.2, the use of data analytics and related technologies are already in place at most European TSO/DSOs, however, automatic managements tools to manage Distributed energy production are often not in place yet (Joint Research Center, 2019). This suggests that digital twins, for the most part, are compatible with existing technologies, values and way of working in the energy sector.

3.1.3. PERCEPTION

Past research studies have defined perception in several constructs. One of the first studies on the relationship between perception and technology adoption explains perception on two constructs: Perceived Ease of Use (PEU) and Perceived Usefulness (PU) (Davis, 1989a). PEU refers to the degree to which an individual believes that using a particular system would be free of effort (Davis, 1989a). Whereas PU is defined as the extent to which a person believes that using a particular system/technology would enhance his or her job performance (Davis, 1989a). All else being equal, a technology/innovation that is high both in PU and PEU is more likely to be adopted within an organization. A third construct of perception described in later literature is Perceived Risk (PR): it is defined as the adopter's (or potential adopter's) perceptions of the uncertainty and the possible un-

Figure 3.2: Digital Twin Compatibility with incumbent technologies (Joint Research Center, 2019)

desirable consequences of using a new technology/innovation (Pavlou, 2003). The role of perceived risk in technology adoption differs across the literature. For instance, as stated in section-2.4.4, one of the drawbacks of the UTAUT technology adoption model is that it does not consider perceived risk as a variable of influence. Some researchers believe that perceived risk directly impacts perceived ease-of-use and perceived usefulness (as an antecedent); whereas others are of the view that perceived risk moderates the effects of perceived usefulness and perceived ease-of-use on behavioral intention to adopt a given technology. Regardless of the role of perceived risk (antecedent or moderator), several studies portray that the level of perceived risk is an essential variable, which together with perceived usefulness/benefits and perceived ease-of-use influences the adoption of a given technology (Naicker et. al, 2016; (I. Im et al., 2008)).

In the context of the energy sector, the usefulness of digital twins for TSO/DSOs include in applications such as: predictive maintenance, accelerated risk assessment, real-time remote monitoring, asset portfolio planning and demand forecasting[1]. For instance, digital twins enable predictive maintenance through which, organizations can proactively identify any issues on their grid and take action before any untoward events (such as: untimely asset breakdown) occur. This also enables TSO/DSOs to more accurately schedule asset servicing and planning, thus lowering their asset (grid) downtime and maintenance costs. Another promising use (benefit) of digital twins in the energy sector is around demand forecasting. Today, TSO/DSOs face significant challenges to predict electricity demand, however, with the use of digital twins TSO/DSOs can simulate various environmental conditions and better predict consumer demand and match with supply at all times. On the other hand, the challenges (risks) found in data analytics, Internet of Things (IoT) and Industrial IoT are similar to those found in digital twins: IT Infrastructure, Useful Data, Privacy and Security, Trust, Standardization and Domain modelling among others (Fuller et al., 2020). Fuller et. al states that without a well-

[1] Source: Article by BearingPoint
Digital Network Twins: Harnessing the power of Digital Twins in the Energy sector

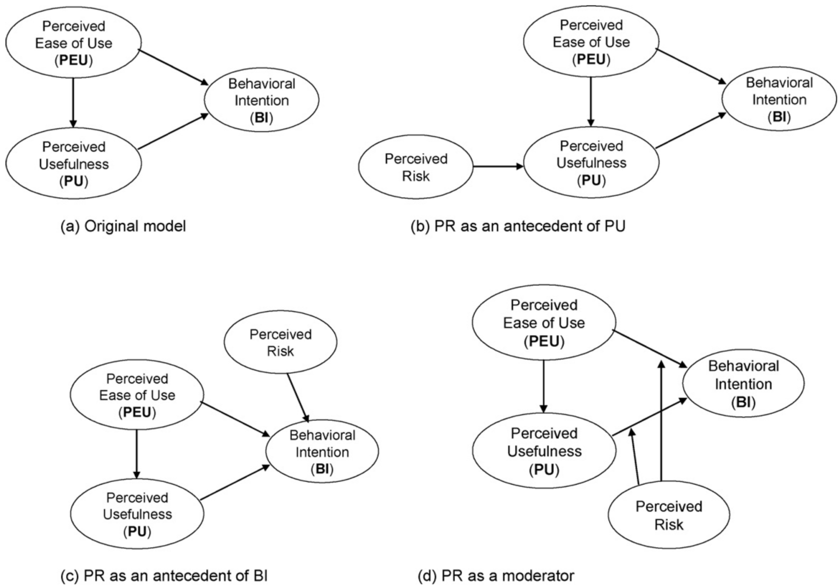

Figure 3.3: The role of Perceived Risk in literature (I. Im et al., 2008)

thought IT infrastructure, digital twins will be ineffective to achieve objectives set-out by the organization. Moreover, if the quality of data is not noise-free, poor or inconsistent, the digital twin could be at a risk of under-performance, again leading to an inability to achieve organizational objectives. Since, digital twins in cetain applications use sensitive energy data of consumers, data privacy, data security and trust come in as potential risks of digital twins. Lastly, at present, there is no standardised approach to digital twins: from initial design to the simulation or deployment phase which can lead to a lot of misunderstanding around digital twins and its risks, benefits or use-cases. Standardised approaches ensure information flow between each stage of the development and implementation of a digital twin. Having said that, the above stated risks and benefits are the risks and benefits of digital twins 'on paper'. When we speak about perceived risks and perceived benefits/usefulness, the element of perception comes into play i.e., the level of the above risks and benefits of digital twins may be perceived differently by different organizations - which is one of the primary focal points of this research.

3.1.4. TECHNOLOGY CHARACTERISTICS

Adopting any new technology in an organization can bring about several new changes based on the nature of the technology. Firstly, depending upon whether the technology is an incremental innovation or a radical innovation for the organization in question, it will have different implications for it. **Incremental innovation**, essentially, builds upon the existing technology and introduces only minor changes to the processes and way of working in the organization (Tushman & Anderson, 1986). Whereas a **radical innovation** is based on a different set of engineering and/or scientific principles and may require

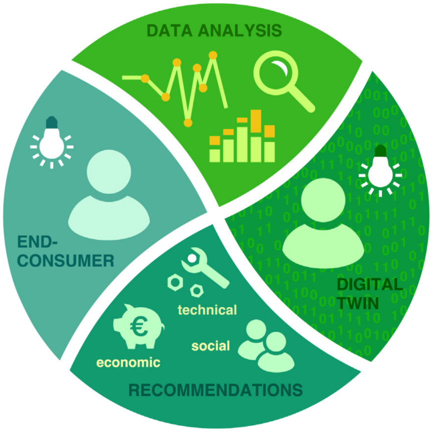

Figure 3.4: Consumer-oriented framework of innovative energy services (Onile et al., 2021)

new ways of working within the organization to manage the new applications that the innovations brings with itself (Dewar & Dutton, 1986). Relative to incremental innovations, radical innovations require more resources, amendments to the existing structure of business operations, and affect more organizational processes- hence, when it comes to technology adoption, radical innovations are more intricate than incremental innovations (Ettlie et al., 1984).

Secondly, a new technology can be more product-oriented or process-oriented for a given organization. **Product-oriented technologies** create new products/services to meet customer needs or market demands. On the other hand, **Process-oriented technologies** focus on improving existing business practices, processes and organizational procedures (Tornatzky & Fleischer, 1990). In general, product-oriented technologies are more easily adopted than process-oriented for several reasons mainly that the latter are perceived to be less valuable as they only support an outcome, whereas, the former is the outcome itself. Moreover, adoption of product-related innovations is easy to implement than that of process-related innovations which tends to require changes in business processes throughout the organization (Tornatzky & Fleischer, 1990).

Thirdly, a technology can be looked at as **Competence-enhancing** or **Competence-destroying** by an organization. The former enable firms to gradually build upon their existing knowledge and processes, while the latter renders existing expertise, technologies and processes in the organization as obsolete (Baker, 2011). In short, organizations must take into account the fact that the characteristics of a given technology will impact both the internal and external attributes of a firm and the industry in which the firm operates in, in turn, influencing its level of adoption.

As depicted in figure-3.4, digital twins in the Energy sector are a part of the larger concept of Innovative Energy Services (IES), that is in turn, based upon a consumer-oriented approach to energy management (Onile et al., 2021). A consumer-oriented model utilizes intelligent components to non-intrusively provide recommendations capable of influencing consumer behavior to adopt energy saving options ((Paukstadt et al., 2019);

(Mrazovac et al., 2012)). In other words, the Innovative Energy Services (IES) approach involves building a digital twin recreation of the end-consumer with the help of data analysis techniques to provide actionable insight/recommendations on the technical, social and economic front to the TSO/DSO responsible for the given electricity grid. Having said that there are three key technologies that enable digital twins, (i.e. enabling technologies): IoT Framework, Advanced Data Analytics and Energy Forecasting Techniques (Onile et al., 2021). The IoT framework that collects data from the physical asset in real-time combined with historic data-set from previous energy consumption are both utilized in the digital twin concept (Ruohomäki et al., 2018). Whether the characteristics of digital twins are perceived by a TSO/DSO as competence-enhancing/destroying or incremental/radical will largely depend on the exact set of technologies being used in their digital twins, overlap with previous procedures/techniques and the application at hand.

3.1.5. AVAILABILITY

Availability is defined as the opportunity, at a micro or a macro level, to materially access technology at reasonable prices, whether at home, at work, at school or in public places (e.g.: public institutions or commercial outlets) (Comunello, 2010). Apart from the fact that, the more available/accessible a given technology is in the market, the easier it is for organizations and/or consumers to use/adopt it, there are other facets to availability. For instance, the availability of complementary products and availability of technical support influences the level of adoption of a given technology. Availability of complementary goods has a positive impact on the overall adoption of technology (Cenamor et al., 2013). Each complementary product unlocks a part of the innovation's overall value (Adner & Kapoor, 2010). An example are translation plug-ins, which act as complementary goods to web browsers - the availability of these plug-ins allows the user to surf and access information in other languages, in turn, increasing the value of web browsers for potential adopters. Hence, widely available complementary products boost the value of a given technology by enabling adopters to exploit more features. Furthermore, potential adopters face market uncertainty if there are many competing technology - adopters cannot predict in advance as to which technology will drive others out of the market (C.-H. Lee et al., 2010). Since, developing complementary products for a given technology by other companies not only requires time, effort and resources, but also trust in its future, higher availability of complementary products signals more confidence in adopters and in the long-term and short-term, in turn, increasing technology adoption (Ceccagnoli et al., 2012). In addition, more recent studies suggest that the availability of technical support facilitates technology adoption. The availability of technical support, shows commitment and social support from organizations to help consumers/adopters tackle challenges such as 'technostress', lack of knowledge, psychological safety among others (Saghafian et al., 2021). In the case of digital twin adoption, the consumers are TSO/DSOs and the technical support ought to come from the vendors that offer to build digital twins.

3.2. ORGANIZATION-BASED VARIABLES

This section outlines the relevant organizational variables associated to Dutch system operators that play a role in digital twin adoption. The organizational-based variables include: Organizational culture, Organizational size, Budget size, Incentives, Management support, Absorptive capacity, (decision-maker's) demographics and attitude towards technology.

3.2.1. ORGANIZATIONAL CULTURE

3

Organization culture is referred to as the collectively held values, shared beliefs and symbolic ideals to which individuals in a given organization ascribe (Melitski et al., 2010). An organization's culture is evaluated on four dimensions: Organizational Climate, Decision-making practices, Leadership and Behavioural outcomes (Melitski et al., 2010). As described in table 3.1, each dimension has certain states that inscribe technology adoption in the culture of an organization.

Organizational Culture	
Organizational Climate	Organization of work Communication flow
Decision-making practices	Influence/control Absence of bureaucracy Coordination
Leadership	Supervisory work facilitation Peer work facilitation
Behavioral outcomes	Job satisfaction Goal integration

Table 3.1: Organizational culture attributes to foster technology adoption (Melitski et al., 2010)

Organizational climate: Organizational climate emerges in organizations by social interaction (information exchange) that scrutinizes the meaning employees attach to the policies, practices, and procedures they experience at work and the behaviors they observe being rewarded and supported (Schneider et al., 2013). There are two constructs within an organizational climate: Organization of work, the extent to which an employee perceives their workplace to be organized in terms of objectives, processes and way-of-working. And, Communication flow, the level to which employees perceive their team/working group to be adequately informed about issues facing the organization (Melitski et al., 2010). Both high levels of organization of work and communication flow are seen as to correlate with high levels of technology adoption.

Decision-making practices: Cultures with high decision-making practices indicate that employees impacted by decisions are asked for input before decisions are made; as a result, in such organizational cultures employees are more willing to adapt and accept innovative ways of working and/or new technologies (Melitski et al., 2010).

Leadership: Employees' perception of supervisory leadership positively influences their willingness to adopt a new technology (Melitski et al., 2010). Put simply, the leadership abilities of supervisors/managers impacts employees, which in turn, influences their behavior towards a technology.

Behavioural outcomes: Employees that are satisfied with their workplace and their organization's culture tend to be open to adopting new ideas and innovations (Dukerich, 2001). Moreover, satisfied employees whose goals are consistent with those of their organization are more willing to adopt a new technology (Melitski et al., 2010).

In short, if employees perceive their firm to be adequately organized, communicate effectively and make informed decisions, then they are more willing to adopt new forms of innovative technologies (Melitski et al., 2010). Hence, organizational culture impacts the willingness of employees to adopt new technology. Therefore, when evaluating the decision to adopt digital twins, management teams of TSO/DSOs should consider the above attributes to determine whether their organizational culture is conducive to the adoption of new technologies like, digital twins.

3

3.2.2. ORGANIZATIONAL SIZE

One of the initial descriptions of organizational size was defined as the number of employees at any given geographical location of the firm (Beer, 1964). Kimberly et. al described organizational size as the organization's resources, transaction volumes or workforce size (Kimberly & Evanisko, 1981). Given the complexity of organizational structures today, we assume that the organizational size is the total number of employees working for an organization regardless of the number of divisions or the number of geographical locations the particular company is based at. There have been several studies conducted in the past to investigate the relationship between the size of an organization and the likelihood of new technology adoption. However, a consistent significant relationship between organizational size and new technology adoption has not been established. In other words, some studies have found a positive correlation between organizational size and technology adoption, others found a negative correlation and some researchers detected no significant correlations between the two. In his empirical studies, Lee et. al revealed that the relationship between organizational size and organizational size had a positive effect on IT innovation adoption, i.e., a larger organization generally adopt more technology innovations than smaller organizations (G. Lee & Xia, 2006). While larger organizations have the ability to deploy more capital for training and other adoption-related activities, they also tend to have more stakeholder opinions (often conflicting) to take into account when making decisions. In short, TSO/DSOs should evaluate the fact that the size of their organization can have influence the adoption of digital twins internally.

3.2.3. BUDGET SIZE

As the name suggests, budget size refers to the amount of capital an organization allocates to technology and related products, systems or services. According to literature, technology (or IT) budget simply refers to technology spending or investment made by an organization ((Ray et al., 2007); (Seddon et al., 2002)). Past research indicates that

Figure 3.5: Organizational size of European TSOs (Total: 43)

small and medium-sized organizations are often confronted in the technology adoption process: limited resources, stretched budgets, lack of technological skills, and insufficient understanding of technology implications lead to headwinds in the adoption process (Heart & Pliskin, 2002). Technology projects are frequently constrained by resources available to the organization, especially the budget to support the adoption. Technology budget size has a great impact on whether organizations can eventually adopt a given technology, irrespective of how beneficial the technology might be to the organization. Therefore, budget size has a positive effect on the overall adoption behavior in the organization (Goode & Stevens, 2000).

Budget size has shown to be positively correlated with technology-related training and procedures which, in turn, enhances technology adoption (Finn et al., 2006). Put simply, organizations with higher budget sizes often invest more towards employee training and related activities when considering new technologies relative to organizations with lower budget sizes; hence leading to higher levels of technology acceptance within their organizations. In addition, several studies in the past have suggested that adequate investment are the foundation of technology adoption ((Bernstein et al., 2007); (Chen & Tsou, 2007)). Furthermore, some researchers also indicate that there is a positive correlation between the size of an organization's technology budget and its technology governance effectiveness (Mohamed et al., 2012). As shown in figure-3.6, European DSOs in 2019 together have invested their budgets the most (in absolute terms) in Smart Grids testing and solutions (Joint Research Center, 2019). As a result, the relevance of digital twin initiatives in such investments cannot be less stated. Therefore, TSO/DSOs must consider their budget constraints when it comes to investments in digital twin initiatives as budget sizes can be expected to play an essential role in their organizational adoption.

3.2.4. EMPLOYEE INCENTIVES

In technology acceptance literature, incentives are considered as an essential instrument for an organisation to aid employee motivation and attitude towards the adoption of

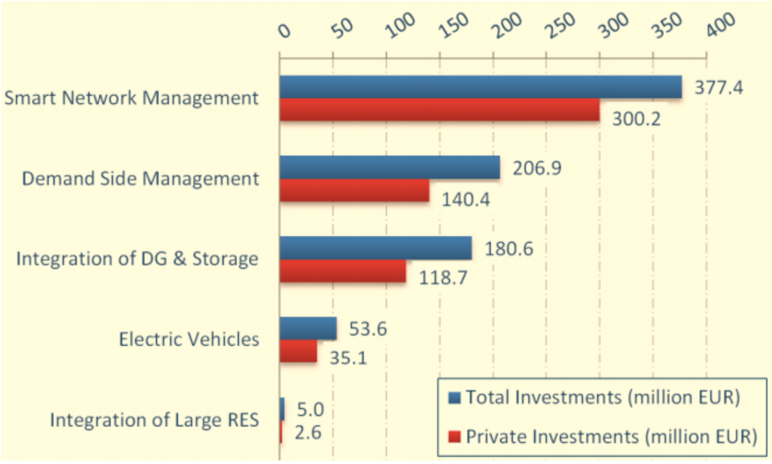

Figure 3.6: Investments in Digtitalization projects (Joint Research Center, 2019)

new technology. Incentive systems are defined as the set of mechanisms through which individual employees or teams are rewarded; they are deemed as an unequivocal statement of an organization's values and beliefs (Kerr & Slocum, 2005). Incentive systems are grouped into two categories: Tangible incentive systems (or hard incentives) and Intangible incentive systems (or soft incentives). Tangible incentive systems are strategic programs for distributing financial rewards, bonuses, promotions and other personal perks and benefits (Li & Roloff, 2007). Whereas, Intangible incentives include non-financial rewards such as recognition, tokens of appreciation, autonomy or job security among others (Milne, 2007). Both tangible and intangible incentives are selectively awarded to employees to acknowledge their behaviour and commitment towards the organisation's values and to positively influence employee attitudes towards management decisions such as the deployment of a new innovation system or technology (Milne, 2007).

Employee incentives influence the infusion or adoption of new information system innovations within an organization (Bhattacherjee, 1998). Incentives are often regarded as powerful motivators of employee behavior towards adoption of a given technology (Nilakant & Rao, 1994). When individual employees act favorably towards the use of new technologies, managers must provide them with incentives such as commissions, recognition and praise to boost the acceptance of the new technology within the organization (Bhattacherjee, 1998). Past studies have found that management support along with incentives are considered as essential factors to ensure smooth adoption of a new technology within an organization. When employees perceive strong managerial support, allocation of sufficient resources and personal benefits behind the use of a new technology, they are likely to develop a positive attitude toward the technology and its usage (Talukder et al., 2008). Therefore, an organization can develop a positive attitude in their employees to adopt the new technology by the means of pre-designed activities such as allocation of (capital) resources and provision of incentives or benefits that employees ought to receive by using the technology such as recognition, bonuses increased autonomy or greater job security (Talukder et al., 2008). Moreover, past research suggests that organizations that do best at digital transformation adoption also do the best job of aligning employee incentives (Fitzgerald et al., 2013). In general both intangible and tangible incentives facilitate intrinsic and extrinsic motivation in employees, however the impact of intrinsic motivation leads to improved organisational innovativeness, which in turn enables the acceptance of new technologies (Behrens & Patzelt, 2018). Therefore, when considering the deployment of digital twins, TSO/DSOs in the Netherlands should ensure that they are in possession of the sufficient resources to also deploy both tangible and intangible incentive systems in order to boost the likelihood of digital twin adoption within their organizations.

3.2.5. MANAGEMENT SUPPORT

Management support is defined as the extent to which leaders in an organization, provide the required support to an operating process and the role of providing explicit directions for the running of a business (Rodríguez et al., 2008). the essence of top management support lies in the degree to which senior leaders in the organization can create a climate of trust, support and performance within the organization. In our case, this would imply that good management teams at TSO/DSOs ensure to arrange resources, capabilities and provide strategic directions to combat any challenges that may come along the path of digital twin adoption within their organization. Since, technological innovation often require commitment of resources, it is essential that the innovation is supported by management teams within the organization (Hossain et al., 2011). Several past empirical studies point towards a positive relationship between top management support and technology adoption (Rouibah et. al, 2009; Ragu-Nathan et. al, 2004; Wu et. al, 2008; Al Haderi et. al, 2018). Moreover, top management support can replace or compensate for a lack of a technology adoption orientation among organizations; thus, when such support is high, the intensity of the direct influence openness of technology adoption increases (Hsu et al., 2019). In the energy sector, there has been a push towards the adoption of digitalization projects/innovations by management teams of grid operators, but so far, there have limited instance, where digital twins have been explicitly stated by management teams. Having said that, there are early adopter TSO/DSOs, where top management support is quite evident. An example of management support is Fingrid's (Finland's TSO) Vice President, who supports the adoption of digital twins not only internally withing his organization, but for the entire energy sector as he explicitly stated that: “To every grid operator hesitant to introduce a digital twin, I say: Don't wait any longer."[2]

3.2.6. ABSORPTIVE CAPACITY

In early research works, absorptive capacity has been defined as the ability to evaluate, assimilate and apply outside technological knowledge to attain commercial objectives (Cohen & Levinthal, 1990). As depicted in fugure-3.7, Cohen et. al deconstruct absorptive capacity into three components: i) **Value Recognition**, ii) **Assimilation**, and iii) **Exploitation**. Value recognition emphasizes that absorptive capacity is path dependent to the firm's prior complementary knowledge and is critical to technology adoption. Sec-

[2] https://new.siemens.com/global/en/company/stories/infrastructure/2018/digital-twin-fingrid.html

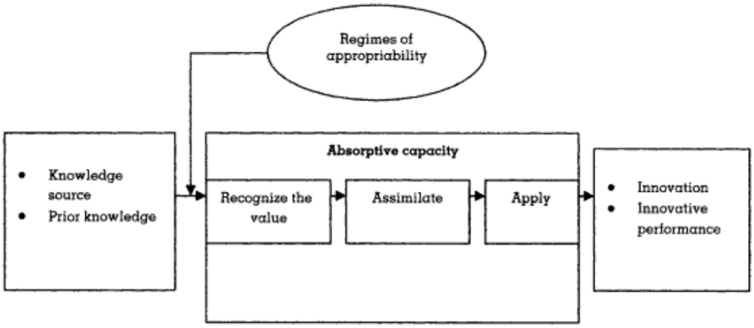

Figure 3.7: Absorptive Capacity model as per (Cohen & Levinthal, 1990)

ondly, Assimilation is the ability of the firm to re-configure and re-deploy resources in order to exploit new external information. Exploitation refers to applying the newly acquired knowledge for the (commercial) benefit to the organization (Cohen & Levinthal, 1990).

On the other hand, the research of (Zahra & George, 2002) defines Absorptive Capacity as a set of organizational routines and processes by which firms acquire, assimilate, transform, and exploit knowledge to produce a dynamic organizational capability (Zahra & George, 2002). Their research points towards the fact that absorptive capacity comprises of two significant sub-components: **potential absorptive capacity** and **realized absorptive capacity** (Zahra & George, 2002). Each sub-component is further divided into two dimensions. Potential absorptive capacity consists of the dimensions of "**Acquisition**" and "**Assimilation**", whereas realized absorptive capacity consists of "**Transformation**" and "**Exploitation**".

Acquisition is an organization's ability to identify and obtain knowledge from external sources (for instance, suppliers or customers) (Flatten et al., 2011). Assimilation refers to a firm's ability to develop procedures in order to analyze, interpret, and understand externally acquired knowledge (Szulanski, 1996). Transformation implies refining the developed procedures to combine existing knowledge with acquired and assimilated knowledge for future use (Zahra & George, 2002). Lastly, Exploitation is the organization's ability to improve and use its existing capabilities, technologies and procedures to build something new based on the 'transformed' knowledge (del Carmen Haro-Domínguez et al., 2007) The central idea behind categorizing absorptive capacity into: potential and realized absorptive capacity is the focus on an efficiency view of absorptive capacity (Gao et al., 2017). In other words, an organization can only transform and exploit as much knowledge as it has acquired and assimilated, and a firm eager to adoption of technologies should aim to maximize the ratio of realized absorptive capacity to potential absorptive capacity.

However more recent research by Todorova et. al questions the soundness of splitting of absorptive capacity into sub-sets of potential and realized absorptive capacity (Todorova & Durisin, 2007). They are of the view that there are ambiguities and omissions that occur by such a categorization especially because the ratio of realized absorptive capacity to potential absorptive capacity is misleading (Todorova & Durisin, 2007). Therefore, when it comes to technology adoption, Todorova et. al proposes to study all the four dimensions of absorptive capacity (Acquisition, Assimilation, Transformation and Exploitation) instead. As a result, in our research, the intention is to measure the absorptive capacity of Dutch TSO/DSOs across these 4 constructs by the means of the scale and (targeted) questionnaire developed by Flatten et. al (Flatten et al., 2011). The questionnaire itself has been further explained in section-4.4. As a final note, absorptive capacity is an essential variable for a company to successfully deploy a new technology at an organization-level (Zahra & George, 2002), i.e., absorptive capacity impacts organizational technology adoption (Mayeh et al., 2016).

3.2.7. DEMOGRAPHICS

Several studies in the past have portrayed a significant role of demographics in the adoption of technology ((Lam et al., 2008); (Meuter et al., 2003); (Parasuraman, 2000)). Demographic variables can include: Gender, Age, Income, Level of Education and Work experience among other factors. Demographic factors are often associated with certain beliefs, and these beliefs mediate adopter attitudes towards technology (Porter & Donthu, 2006). Findings about the influence of demographics on technology adoption are sparse or inconsistent ((Dabholkar & Bagozzi, 2002); (S. Im et al., 2003)). In other words, the influence of demographic variables will differ on a case-by-case basis given different contexts and technologies at hand. Put simply, it cannot be generalized that younger employees in any organization are more likely to adopt a given technology relative to older employees, for instance. Or, highly-educated workers in any organization are more open to using technologies when compared to low-educated workers. Having said that, demographics play an essential role in influencing the levels of technology acceptance in an organization. For TSO/DSOs, this implies that management teams should account for their employee demographics when considering investments in digital twins. Management teams ought to investigate the adoption of prior technologies/innovations within their organization across varying (employee) demographic characteristics. This would enable TSO/DSOs, to some extent, forecast technology-usage levels, reactions and responses in employee groups/departments once the decision to deploy digital twins is made.

3.2.8. ATTITUDE

As per the regulatory focus theory, an individual possess two motivational systems: promotion and prevention systems (Higgins, 1997). These motivational systems are based on the behavioral patterns of an individual, their natural state and can also vary based on cultural factors, in turn, perceiving one to achieve pleasure or avoid pain in the same set of circumstances and/or conditions. However, in general, prevention-focused decision makers are less likely to be concerned about the potential positive outcomes of their decision and focus more on the probability of a negative outcome. Whereas, promotion-focused decision makers are less likely to be concerned about the possibility of negative outcomes and tend to give more importance to the probability of positive outcomes (Scholer et al., 2014). In terms of technology adoption, prevention-focused decision makers are more sensitive to whether early adoption of new technologies can pose risks for organizational performance. On the other hand, promotion-focused decision makers are more sensitive to how new technologies can increase organizational performance (K. Lee & Joshi, 2018). Given the fact that digital twins are still in their infancy in terms of adoption rates, prevention-focused decision-makers will be risk-averse and favor an alternative that has been tried and tested over several repetitions until digital twins are widely adopted. Hence, prevention-based decision-makers have a higher probability to implement exploitative strategies, whereas, promotion-based individuals prefer exploratory strategies when it comes to technology adoption (K. Lee & Joshi, 2018).

The decision-makers' attitude whether promotion-based or prevention-based, is a relevant adoption variable, however, not the sole determinant of whether the organization will adopt a given technology. This may seem counter-intuitive at first, as one may tend to think the decision-maker has the final say whether an organization adopts a technology or not. To make this point clear, consider the following: if a decision-maker has a promotion-based attitude towards a given technology, but, contextual variables are not conducive to adopt the technology, it might be unlikely that the decision-maker will take the decision to adopt it. For instance, if the perceived risks outweigh the benefits, or if the technology requires capital investments that lie outside the budget of the firm, the decision-maker might decide to not adopt the technology, even though he has a promotion-based attitude towards it. Similarly, given the contextual variables and situational information at play, a prevention-based risk averse decision-maker might as well adopt a given technology. Therefore, the adoption of digital twins at a TSO/DSO is a combination of both the decision-maker's attitude towards digital twins and contextual factors such as company objectives, perceptions and capital requirements to name a few.

3.3. EXTERNAL VARIABLES

The relevant factors that are associated with the external environment and the broader energy sector when it comes to the adoption of digital twins include: **Regulations**, **Competitive behavior** and **Network effects**.

The role of **regulations** in technology adoption cannot be less stated. Regulations have the ability to both beneficially slow technology adoption or fasten technology adoption in an industry. Regulations can discourage an organization from preemption as to change the order in which firms adopt new technologies, speeding one firm's adoption rate and slowing the other's (Riordan, 1992). Whereas, on the other hand, policies can also be designed in a manner that encourages organizations in a given industry to pursue the adoption of new innovations for numerous environmental, economical and societal reasons. Policies set by governmental bodies, regulatory authorities and other policy-makers can have an impact on industry-wide technology adoption or only influence a sub-sector in an industry. For instance, policy analysts suggest that the Data Governance Act (DGA) by the European Union could act as an enabler for the adoption of digital twins as DGA could possibly increase the availability of fully secure, trusted and quality data in both the public and private industries[3]. Therefore, TSO/DSOs should analyze the current policy environment and related dynamics to assess whether investments in digital

[3] https://www.digitalurbantwins.com/post/data-governance-act-practical-implications-for-digital-twins

twins may lead to headwinds or tailwinds for their organization.

A second external variable relevant to technology adoption is **competitive behavior** by organizations in an industry. In times when there are several uncertainties associated with an emerging technology, firms may tend to delay the adoption of the technology in order to acquire more information and learn from the experiences of competitors who were early adopters (Hoppe, 2002). In other times, delaying the adoption of a technology may cause an organization to lose out on the first-mover advantages of adoption to its competitors (Hoppe, 2002). In addition, firms can also introduce lags between adopting a technology and declaring the profitability to the technology, in order to create uncertainty and reduce the adoption levels at competing firms. Hence, TSO/DSO should take into account the perspective of competitive behavior by other TSO/DSOs when looking at digital twin adoption.

Lastly, technology adoption in organizations are subject to **network effects** (Weitzel et al., 2000). Network effects have been defined as the change in the benefit that an entity derives from a good when then number of entity consuming a similar good changes (Liebowitz & Margolis, 1995). Conventional technology adoption models as described in section 2.4 only partly capture the influence of network effects on technology adoption (leaving out their dynamic nature) (Beck et al., 2008). There are two types of network effects: direct and indirect. Direct network effects are the direct "physical effects" of being able to exchange information and indirect network effects, arise from interdependencies in the consumption of complementary goods (Katz & Shapiro, 1985). Both direct and indirect network effects influence technology adoption, however, research suggests that direct network effects are primarily the drivers of both early and late phases in the adoption process (Beck et al., 2008). Direct network effects drive technology adoption in the early phases by spreading awareness and positive expectations of the technology to combat the uncertainties associated with new technologies (i.e., start-up problem). As a result, TSO/DSOs should keep in mind the presence of network effects in their organization or the industry at large when considering digital twin adoption.

3.4. Operationalization, Selection & Exclusion criteria

Thus far in the chapter, variables that influence the adoption of digital twin were investigated. This section excludes, selects and operationalizes variables that will be the focus of the remaining study going forward.

- **Absorptive Capacity**: As mentioned in section-3.2.6, absorptive capacity has been classified into three dimensions: identify, assimilate and exploit in literature. In more recent literature, however, Zahra and George (2002) broaden absorptive capacity intro four dimensions: acquire, assimilate, transform, and exploit as most knowledge that an organization wishes to exploit which is available externally must first be converted/transformed into a usable form. Absorptive capacity was selected as a variable of interest due to its feasibility of measurement across all four dimensions in an organization. Flatten et. al has developed a multi-dimensional questionnaire and a measurement scale to assess absorptive capacity within an organization (Flatten et al., 2011), which is further discussed in next chapter.

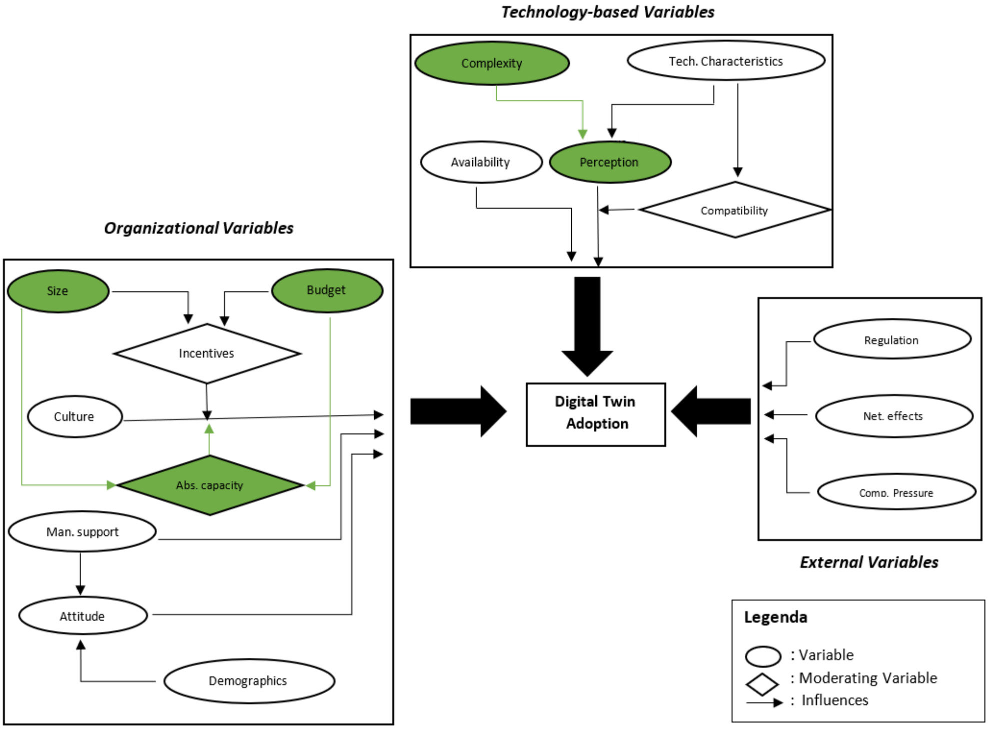

Figure 3.8: Conceptual Model: Digital Twin Adoption

- **Budget size**: Since, every organization (TSO/DSO) has different budget expenditures for digitalization projects, more specifically for digital twins, it is challenging to find specific budget allocation numbers towards digital twins in these organizations. In addition, the organization's financial statements are also not required to report 'digital twin' budget expenses as such, however, all public organizations are required by law to report net profit figures. Hence, net profit was used as a proxy for digital twin budget size in our research. The underlying assumption is that the larger the net profit, the more monetary 'space' an organization has to invest in digitalization projects like digital twins given most funding is sourced internally. Having said that, net profit would be the closest proxy to measure budget size relative to other line items on the financial statements. For instance, revenue cannot be considered a good proxy as there could be additional costs that a TSO/DSO incurs which might leave less monetary 'space' for digital twin investments. Apart from the ease of assessment, budget size has been selected because the Dutch TSO/DSOs are on the spectrum from low-to-high budget sizes. Observing the differences that arise in digital twin insights due to these differing budget size is an interesting aspect to investigate.

- **Organizational size**: Alike budget size, organizational size is easy to measure in terms of available human resources. Of the eight Dutch TSO/DSOs, there are diverse organizations with different organizational sizes - some larger, whereas others mid-sized and others small-scale. Organizational size has been operationalized in terms of the number of full-time employees (FTEs) that are employed at a particular TSO/DSO. The objective is to assess differences in the perception of digital twins between TSO/DSOs of different sizes.

- **Employee incentives**: The assessment criteria to award employees with incentives in an organization are often not clear enough and contain vague indicators which time and again leads to a lack of transparency ((Wenzel et al., 2019); (Bol et al., 2016); (Castilla, 2015). Given the lack of transparency and vagueness around employee incentives, this variable was excluded from further research in the thesis.

- **Culture**: Organizational culture is amorphous, difficult to measure and quantify especially with objective indicators (Hoffman & Klepper, 2000). Furthermore, culture is subjective and can have different meanings to different employees all within the same organization. A qualitative interview of 30 minutes would also not do justice to measure the culture of an organization - for this reason culture will has been excluded and will not be the focus of the rest of our research.

- **Management support**: Top management support has been excluded from further research/thesis for operational reasons, namely, it was foreseen and expected to be difficult to reach management level teams given their busy schedule. Although, eventually is was managed to interview one person in the management team, but that would, by far, not be enough to draw judgements for management support to digital twins across the energy sector.

- **Attitude**: Although the individual's attitude is a relevant variable for technology adoption in an organization, yet attitude was excluded from further investigation in the context of this thesis as the level of analysis of the research being at firm level rather than individual level.

- **Demographics**: Demographics has been excluded from further investigation in the thesis as the author expected to be unable to find interviewees of diverse demographics such as Age, Gender and Level of Education to name a few. All participants had to have the ability to influence technology adoption within their organization either thought position and/or expertise. Since, most technology adoption decision-makers within TSO/DSOs tend to be highly experienced and/or highly-educated, it would be rather challenging to draw generic conclusions based solely on demographics without introducing bias or skewness (towards highly-educated and experienced) to the data collection process.

- **Complexity**: Complexity was included as a 'known variable' going forward. Since, complexity of digital twins can vary per application and per TSO/DSO, we make an assumption of using digital twins in the application of simulating an entire network. Therefore, a proxy for measuring the complexity of digital twins is circuit (grid) length. The grid length (or circuit length) is a structural characteristic of a grid which is a summation of the number of kilometres of AC lines, AC cables and DC cables that a TSO/DSO oversees (ENTSO-E, 2019).

- **Perception**: As one of the objectives of this research is to understand the (current) sentiment towards digital twins in the energy industry, selecting perception as one of the variables to be investigated further was a clear-cut decision to make. Digital twin perception is considered to be an unknown variable as it cannot be determined via desk research and included a comprehensive set of aspects such as: awareness of digital twins, potential use-cases, motivation/factors of interest, stage of development, potential impact on current operations, risks, sector-wide challenges, suppliers, vision of the organization/digital twins and implementation decision.

- **Availability**: As discussed in section-3.1, availability has mostly to do with the availability of digital twins in the market, availability of complementary goods and availability of technical support. To get a better view on all, if not most, of these aspects would require us to go into discussions (conduct interviews) with suppliers and vendors of digital twins rather than the TSO/DSOs themselves. Keeping our focus central on TSO/DSO rather than the suppliers, it was decided to exclude availability from further research in the thesis. Having said that, there have been questions included in the interview that give an indication of availability. For instance, the question whether they are aware of suppliers/vendors of digital twins. One must keep in mind that, this only gives us an indication of availability: more precisely, the vendor awareness level of the participant might not be indicative of the market availability of digital twins. Hence, as much a relevant variable availability is, the decision to exclude it from the research/thesis further was made.

- **Compatibility**: Compatibility was excluded further in this study with the reason that it requires to investigate the technicalities of existing technologies/procedures and practices (outside the scope of the thesis) used by TSO/DSOs to make calls on whether they are compatible with digital twins.

- **Technological characteristics**: As discussed earlier, technological characteristics are certainly a relevant factor for adoption. However, as mentioned in section-1.2, investigating technicalities, technological characteristics and/or architectures in depth lies outside the scope of this thesis.

- **External variables**: Regulation, Network effects and Competitive behavior were all excluded further in this thesis as the focus remains on TSO/DSOs rather than governmental authorities, policy-makers and other regulatory bodies.

3.5. CONCLUSION

In this chapter, variables that are relevant to adoption of digital twins in the energy sector were delineated; based on the existing nature of literature, there are five technology-based variables, eight organizational-based variables and three external variables. Each variable was described and its relationship with technology adoption was also narrated as per past academic studies. Of the many variables, it was concluded that the variables of focus for the remaining research will be: Absorptive capacity, Organizational size, Budget size, Complexity and Perception. This was done it order to limit the scope of the study with the principal inclusion criteria being feasibility of measurement. Organizations size, Budget size and Complexity are the so-called known variables as they are measured/observed by the author via desk research. To operationalize these variables, the number of full-time employees (FTE), net profit and grid circuit length were used as proxies. Whereas, perception and absorptive capacity are 'unknown variables' and the intention is to measure these variables by conducting (semi-structured) interviews and sending targeted questionnaires to technology adoption decision makers within Dutch TSO/DSOs respectively: the process will be discussed in detail in the next chapter.

4

Research Design & Empirical Analysis

In the previous chapter, it was determined that of the many adoption variables the focus of the thesis going forward is on select variables: Absorptive capacity, Organizational size, Budget size, Complexity and Perception. This chapter begins with an empirical analysis of the organizational characteristics (known variables) of the TSO/DSOs and a brief description of the study participants. Then, it deciphers the research design of the semi-structured interviews and the targeted questionnaires. Lastly, the chapter ends by narrating the data management process adopted by the author to account for the privacy of the individual participants taking part in this research.

The research methods primarily adopted in this chapter are: **Desk research** of secondary data sources, **Semi-structured interviews** and **Targeted questionnaires**

4

4.1. DUTCH ELECTRICITY SECTOR

In this section, the author describes the landscape of the Dutch energy sector and conducts an empirical analysis of the organizational characteristics of the TSO and DSOs in the Netherlands. The study is aimed at participants of the Dutch Electricity sector, who mostly operate on the transmission and distribution side of the network. As shown in figure-4.1, an electricity grid consists of three parts before it can reach the end consumer. The first part, is power generation which involves producing electrical energy usually by converting from other forms of energy. For instance, a wind-power plant will convert wind energy to electrical energy in this phase. After the electricity has been produced, it goes through a step-up transformer which increases its voltage levels allowing it to travel over long distances. Second, Transmission System Operators (TSOs) control the the high voltage parts of the grid and move large amounts of power over long distances to the distribution networks. Third, once the power reaches distribution networks, Distribution System Operators (DSOs) use a step-down transformer to lower the voltage levels and transport the electricity to the end consumer. Hence, DSOs move smaller amounts of power (in terms of voltage) at shorter distances to the consumer.

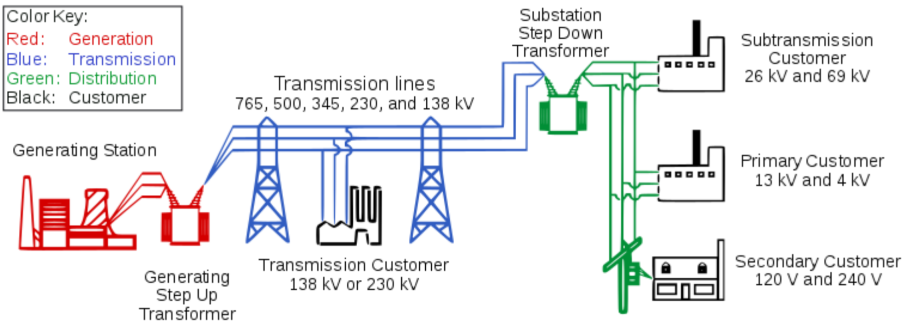

Figure 4.1: A simplified Electricity Grid (Source: US Department of Energy)

In the Dutch Electricity grid, there are eight companies that operate on the Transmission and Distribution networks which shown in the list below. The participants of the study included all of them excluding Cogas Infra en Beheer B.V and Enduris B.V due to their unavailability for an interview.

- One Transmission System Operator (TSO): TenneT
- Seven Distribution System Operators (DSOs)
  - Stedin B.V.
  - Alliander (Liander N.V)
  - Westland Infra Netbeheer
  - Enduris B.V.
  - Enexis B.V
  - Rendo Groep

– Cogas Infra en Beheer B.V (Coteq Netbeheer)

As mentioned in section-3.4, organizational size was operationalized based on the number of employees working at the company, budget size based on the company's net profit and grid (circuit) length for complexity. These variables (organizational characteristics) were further used to categorize TSO/DSO in the Netherlands.

Based on the number of full-time employees picturized in figure-4.2, four large players in the Dutch market are observed namely, Alliander (5786 FTE), Enexis (4767 FTE), Stedin (3532 FTE) and TenneT (3409 FTE). Then, Enduris (650 FTE) which is now a part of the Stedin Group. Finally, the other smaller DSOs with less than 250 employees each: Westland Infra (213 FTE), Cogas Infra en Beheer (171 FTE) and Rendo Groep (125 FTE). Hence, based on organizational size, the largest DSO is Alliander, followed by Enexis and Stedin. Whereas, the smallest DSO, by far are: Rendo, Cogas Infra en Beheer and Westland Infra.

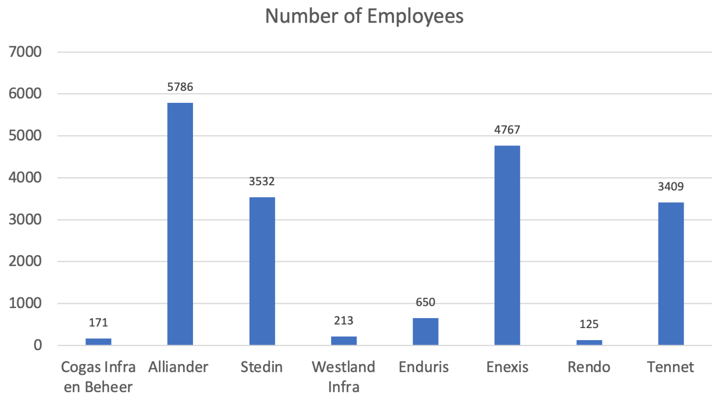

Figure 4.2: Dutch TSO/DSO per Number of employees

When looking at annual net profit, TenneT is the most dominate player in the market with a profit of 837 million Euros in 2020. This exorbitantly high net profit relative to other participants can be regarded to the fact that TenneT is a TSO, implying that it operates on the high voltage (HV) parts of the electricity grid which tend to be more expensive to manage and have higher revenue streams because TenneT playing the role of a TSO transports electricity to DSOs, eventually to the end consumer. So, in a certain sense, TSOs play a critical role in managing the electricity grid of their country – any mishaps on their end can cost/lead to outages in major parts of the country. Furthermore, TenneT not only operates in the Netherlands, but also manages a part of the German Electricity grid, which also leads to a highly skewed net profit when compared to DSOs in the Netherlands.

As shown in figure-4.3, Alliander is the DSO with the highest net profit at 224 million euros in the last financial year. Followed by Enexis at 108 million euros and Stedin at 42 million euros. Like organizational size, the largest TSO/DSO in terms of net profit also are the same four players: TenneT, Alliander, Enexis and Stedin. The other four DSOs

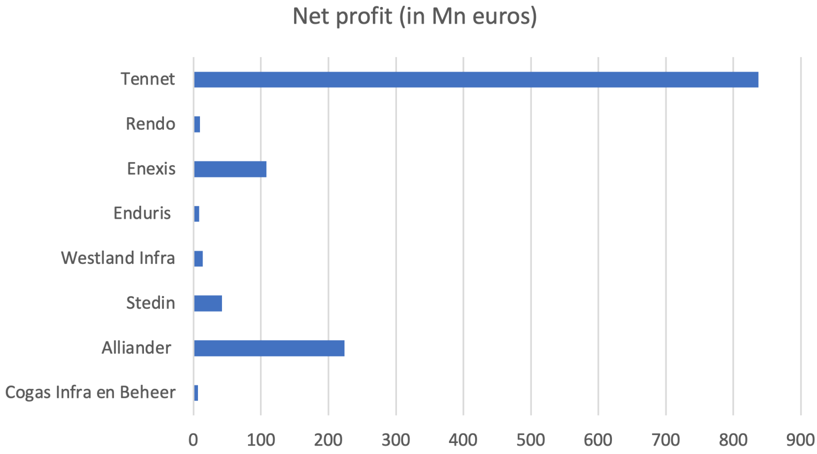

Figure 4.3: Dutch TSO/DSO per Annual Net profit

have an annual net profit of less than 15 million euros – Westland Infra (13,8 million euros), Rendo (9,5 million euros), Enduris (now part of Stedin Group: 8,4 million euros) and Cogas Infra en Beheer (6,8 million euros). Therefore, as our measure/proxy of digital twin budget size is annual net profit, TenneT is expected to have the highest budget allocations for innovative technologies like digital twins, followed by Alliander, Enexis and Stedin.

A proxy of complexity of grids managed by a TSO/DSO is the grid length. The grid length (or circuit length) is a structural characteristic of a grid which is a summation of the number of kilometres of AC lines, AC cables and DC cables that a TSO/DSO oversees (ENTSO-E, 2019). As presented in figure-4.4: based on the length of the grid/circuit managed, Enexis (142.200 km) is the largest player, followed by Alliander (92.000 km), Stedin (56.854 km) and TenneT (23.000 km). A point to be noted here is that most cables/lines that TSOs (TenneT in this case) oversee are high-voltage, whereas, DSOs have mostly Medium-Voltage, Low-Voltage, but also a few high-voltage lines – this is due the fact that DSOs transport electricity directly to the end user. Therefore, the grid length of TenneT appears to be lower than other major DSOs. Just like the prior instances of organizational size and annual net profit, the smaller DSOs by grid length in this case are also the same: Enduris (now under Stedin: 9617 km), Westland Infra (2845 km), Cogas Infra en Beheer (1353 km) and Rendo (901 km). In relative terms, it can observed that Enexis, Alliander and Stedin oversee and/or manage approximately 88% of the Dutch Electricity distribution grids. Whereas, the smaller DSOs: Westland Infra, Enduris (now part of Stedin), Rendo and Cogas Infra en Beheer account for overseeing only about 5% of the Dutch distribution grid. Therefore, these smaller DSOs are certainly critical regional players, but might have and/or exert limited impact on the grid at the national level.

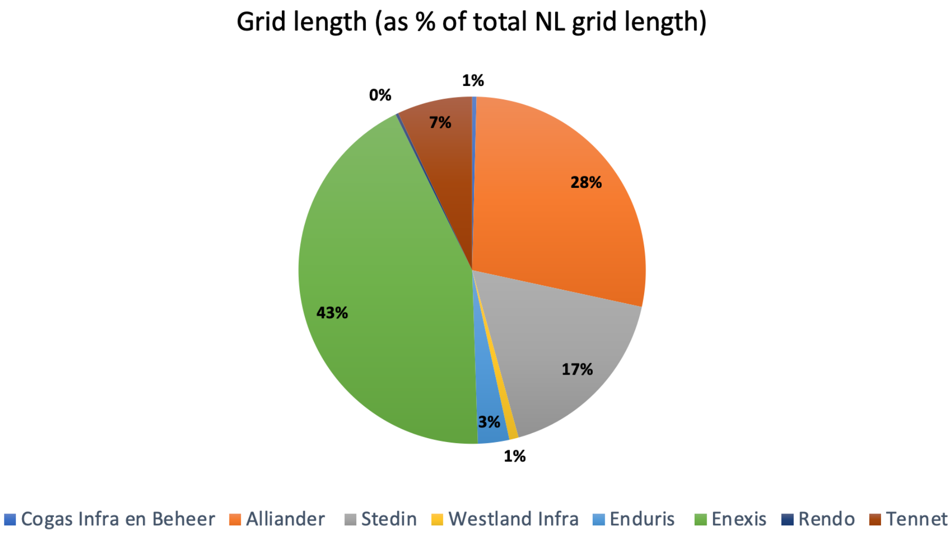

Figure 4.4: Dutch TSO/DSO per Grid length

Organizational Size	Budget size	Grid Length	Participant
Small Organizational size	Low Budget size	Low Grid Length	Cogas
		High Grid Length	Enduris
	High Budget size	Low Grid Length	Rendo Groep
		High Grid Length	Westland Infra
Large Organizational Size	Low Budget size	Low Grid Length	Stedin
		High Grid Length	Enexis
	High Budget size	Low Grid Length	TenneT
		High Grid Length	Alliander

Figure 4.5: Classifying the Dutch TSO/DSO landscape

Given the clear contrast between larger TSO/DSO and smaller TSO/DSO in terms of organizational size, budget size and grid length, the study participants were classified in a 2x2x2 matrix as represented in figure-4.5. The matrix is to be interpreted in a relative manner - for instance, within smaller organizations, there are two organizations with a low and high budget each; further, within smaller organizations with high budget, there is one organization each with high and low grid length. In other words, when it is said TenneT has a low grid-length it implies a lower grid length relative to Alliander and not for instance, Westland Infra. Such a relative matrix style has been adopted to categorize and anonymize the participating TSO/DSOs.

Research Participant Profile			
TSO/DSO	**Work Experience**	**Gender**	**Role (Anonymized)**
Large-sized TSO/DSO with low budget-size and low grid-length *(3 participants)*	10 - 20 years 10 - 20 years 20+ years	Male	- CXO - Director - Member Management team
Large-sized TSO/DSO with low budget-size and high grid-length	1 - 5 years	Female	- Innovation Researcher
Large-Sized TSO/DSO with high budget-size and low grid-length	10 - 20 years	Male	- Director
Large-sized TSO/DSO with high budget-size and high grid-length *(2 participants)*	1 - 5 years 10 - 20 years	Male	- Consultant - Architect
Small-sized TSO/DSO with high budget-size and high grid-length	10 - 20 years	Male	- Director
Energy Supplier	5 - 10 years	Male	- Manager Innovation

Figure 4.6: Research participants - Profile

4.2. STUDY PARTICIPANTS

Of the above mentioned organizations, there were a total of 9 participants who represented the energy companies and took part in this research. There was representation from all the TSO/DSO except for Cogas, Enduris and Rendo Group. The author was unable to get in touch with Cogas and Enduris successfully, whereas Rendo declined to participate in the research on the grounds of limited awareness of digital twins within their organization. Moreover, there was also one interviewee working at an an energy supplier. As shown in Figure-4.6, the participants were well-distributed across age-groups in terms of their experience in the energy sector.

Despite the diversity in experience levels, unfortunately, there was limited diversity in participants when it comes to gender. The interviewees with the following (anonymized) roles took part in the research: Chief X Officer, Director, Innovation Researcher, Directors, Business Consultant, Innovation Manager and Architects. The criteria for selecting participants was that he/she had to have the ability to directly influence the adoption of a new technology within their organization either through their role/position or through expertise/knowledge. In order to keep the anonymity of the participants in tact, the author has not linked the work title (role/position) with the participating organization. As a side note, participants were reached via the network of BearingPoint and some were approached directly by the author via social-media platform, LinkedIn.

4.3. INTERVIEWS

In this section, the (structured) questions that were asked to the participants during the interview are presented. There were a total of 10 questions asked to the participants that ranged from more abstract questions like: what a digital twin is to more concrete questions along the lines of who the suppliers are. The questions are on the spectrum from digital twin awareness/perceptions to digital twin adoption and are as follows:

1. **A digital twin is a virtual replica of any physical asset. How does your organization see what a digital twin is?**
   This question aims at judging the level of (digital twin) awareness of the participant. Since most, if not all, of the selected interviewees have the ability to influence the adoption of any given technology in their organization either by their role or expertise the importance of this question cannot be denied. If the interviewee (i.e. technology adoption decision-maker) portrays a good understanding of digital twins, it could suggest that the organization has at least considered digital twins in their strategic and/or operational conversations. On the other end, if the interviewee has not heard about digital twins, this may suggest limited awareness of digital twins in their organization.

2. **In your opinion, what would be the potential digital twin use-cases for your organization?**
   This question is aimed at revealing whether the participant's organization has already thought of potential use-cases that align with their operations and mainly to gather insights on how TSO/DSO see digital twins contribute to their current way of working.

3. **Why is your organization interested/motivated to consider investing in Digital Twins?**
   This question is designed to reveal the factors of interest and/or motivation that the decision-maker considers relevant for their organization when it comes to digital twin adoption. These factors of interest, in a certain sense, (will act as) the drivers of digital twin adoption within the organization. The core question that is expected to be answered here is essentially: why have digital twins sparked the interest of TSO/DSO and what do they expect to achieve from them.

4. **How far are you in the development of a twin / implemented digital twins in operations already? Why?**
   This question is aimed at discovering the initiatives that the interviewee's organization has already taken or is planning to take towards the adoption of digital twins, in turn, assessing their level of adoption/development stage. Examples of some initiatives could include: pilot projects, research studies, university collaboration, case-studies among others. Another piece of information that could be uncovered with this question is to understand what aspects the organization considers to be missing in case of slow adoption; or the success factors in the case of quick adoption

5. **How could you describe the (potential) impact of digital twins on your existing company processes/applications?**
   Based on the prior digital twin initiatives taken in the organization, this question aims to capture the learnings that the interviewee has experienced or realized already and how digital twins have impacted their processes, way of working or are expected to further do so.

6. **What are your thoughts on the risks and benefits of digital twins? Given equal risks and benefits, would you or not take the decision to use them?**
   The objective of this question was to gather insights on the perceptions of a digital twin and what the participant and/or the organization sees as major risks that hinder their adoption.

7. **In your opinion, what are the challenges to digital twin adoption in the Energy sector?**
   With this question, the aim is to discover the challenges that are faced by TSO/DSOs and the Dutch energy sector in general around the adoption of digital twins.

8. **Are you aware of any suppliers who can implement digital twins for your organization? Have you contacted them?**
   Implicitly the above question aims to provide insights into the development stage of a given TSO/DSO (i.e. are they in research phase or close to first steps in deployment?). Explicitly the question assesses the awareness levels of a TSO/DSO when it comes to sourcing.

9. **What is the vision of your organization and how does it align with the adoption of digital twins?**
   The goal of this question is to collect insights into how TSO/DSOs see the future of large-scale digital twin adoption in the energy sector and to discover whether they have put thought into how digital twins align (or not) with company strategy.

10. **If the decision to implement digital twins in your organization today was solely in your hand, would you, do it?**
    This may seem like an unrealistic question at first sight due to the fact that in practice, the decision to adopt any given technology in an organization is unlikely to be the sole responsibility of a single employee/person. However, the questions aims to assess the attitude of the interviewee (i.e., technology adoption decision-maker) when it comes to the adoption of digital twins in his/her organization and his/her aversion to uncertainty and risk given that the large-scale adoption of digital twins is still in its infancy.

4.4. TARGETED QUESTIONNAIRES

To assess the absorptive capacity of the TSO/DSO at hand, a targeted questionnaire was sent to the participants as a follow-up action after having conducted the interview. The questionnaire used was adopted from the research of Flatten et. al, who devised a scale to measure organizational absorptive capacity. The questionnaire consisted of 14 statements measuring organizational absorptive capacity across four dimensions: **Acquisition**, **Assimilation**, **Transformation** and **Exploitation** (Flatten et al., 2011); and each statement was rated between (1-5) (Strongly Disagree, Somewhat Disagree, Neutral, Somewhat Agree, Strongly Agree). Flatten et. al defines Acquisition as an organization's ability to identify and obtain knowledge from external sources (for instance, suppliers or customers). Assimilation refers to a firm's ability to develop procedures in order to analyze, interpret, and understand externally acquired knowledge (Szulanski, 1996). Transformation implies refining the developed procedures to combine existing knowledge with acquired and assimilated knowledge for future use (Zahra & George, 2002). Lastly, Exploitation is the organization's ability to improve and use its existing capabilities, technologies and procedures to build something new based on the 'transformed' knowledge (del Carmen Haro-Domínguez et al., 2007). For a more detailed description of the specific questionnaire statements, please refer to Appendix-B.

An organization is considered to have a high absorptive capacity in a given dimension (Acquisition, Assimilation, Transformation or Exploitation), if the respondent marks Somewhat Agree or Strongly Agree in the majority of the statements in the respective (dimension) block. In other words, for an organization to be deemed as having high absorptive capacity, an example response of the participant may look like this: -

- **Acquisition:** 2 out of 3 statements have somewhat agree or strongly agree (2/3)
- **Assimilation:** 3 out of 4 statements have somewhat agree or strongly agree (3/4)
- **Transformation:** 3 out of 4 statements have somewhat agree or strongly agree (3/4)
- **Exploitation:** 2 out of 3 statements have somewhat agree or strongly agree (2/3)

In addition to the statements of the questionnaire from (Flatten et al., 2011), the author included a couple of more questions related to the adoption of digital twins in the questionnaire. The additional questions, in a certain sense are similar to the ones asked in the interviews, but with the aim to quantify them and were as follows: -

- ***Questions related to participant data:***
  1. **Which energy market participant do you work for?**
     To answer, the participant selected his/her company from a drop-down menu listing all the TSO/DSOs in the Netherlands
  2. **What role (title) are you responsible for within your organization?**
     To answer, the participant simply filled in his/her work title in a field
  3. **How many years of total work experience do you have in the Energy & Utilities industry?**
     To answer, the participant selected from the following options: 1-5 years, 5-10 years, 10-20 years or 20+ years
- ***Questions assessing Digital Twin Awareness***

1. **When did you first hear about digital twins and how? (e.g. In 1920 from a research paper)**
   To answer, the participant simply filled in his/her 'first' source of information around digital twins.
2. **Please state below examples of digital twin applications and/or use-cases that you feel are promising for your organization**
   To answer, the participant simply filled in a potential use-cases of digital twins for his/her organization.
3. **What do you feel are the biggest barrier(s) when it comes to digital twin adoption? (Multiple answers allowed)**
   To answer, the participant selected from the following options: High Investment costs, Uncertainty around added value, Regulation, Uncertainty around risks, Limited availability, Complexity, Compatibility. Limited knowledge within organization and Others.

- ***Questions assessing Budget allocations***

  1. **Do you have budget allocations towards digitalization and/or innovation projects other than digital twins?**
     To answer, the participant selected the options: yes or no.
  2. **Do you have budget allocations specifically towards digital twin projects?**
     To answer, the participant selected the options: yes or no.
  3. **Do you already have digital twin pilot projects running in your organization?**
     To answer, the participant selected the options: yes or no.
  4. **If the decision to deploy digital twins in your organization on a large scale was solely in your hand, would you do it?**
     To answer, the participant selected the options: yes, no or cannot say

4.5. DATA MANAGEMENT PROCESS

In order to manage any data that is received from primary sources, in this case, from the participants of the research study, a three-step data management process was devised.

1. **Human Research Ethics Committee (HREC) Approval**: Firstly, the objectives, research questions, research methods and a short description of the research was shared with HREC for an approval for conducting the research on human participants. Only after the approval of the HREC committee, interviews with external participants were conducted.

2. **Informed Consent Form**: Prior to the interviews, participants were asked to fill-in an informed consent form in which they agreed to the terms and conditions for their participation in the study and the use of their data. Among other things, the form included the fact that the participation is entirely voluntary and a participant can withdraw at any time and is free to omit any question either in the questionnaire or during the interview. Any data that the participants provide, will be used

within the bounds of the research i.e., for validating the conceptual model and generating insights to answering the research question(s). Furthermore, the participants were informed that the interviews will be recorded only for the purpose of processing the information collected during the interview.

3. **Surf-Drive**: In order to protect the privacy of the interviewees and considering the GDPR guidelines, the video recordings of the interview were stored on a restricted TU Delft online SURFdrive for a maximum period of one month with access to only the author and the university supervisors. One month after the interview, the recordings were deleted and the interviews were transcribed into text in an anonymized manner to be included in the appendix of the thesis.

Lastly, but most importantly, at the start of every interview, explicit permission to start interview recording was requested from every interviewee. At the end of the research period, all the collected data is to be deleted in order to minimize any risk of data breaches that may occur from online activities. Having said that and as mentioned earlier, the thesis will be publicly available at the end of the thesis period with the meta-data associated with interviewees anonymized.

4.6. CONCLUSION

In this chapter, an empirical analysis of the organizational characteristics of TSO/DSOs in the Netherlands was conducted. The empirical analysis included an investigation into the 'known variables': organizational size, budget size and complexity, which were observed by using number of full-time employees (FTE), net profit and grid length as respective proxies. Based on the outcome of the analysis the TSO/DSOs in the Netherlands were categorized into a 2x2x2 relative matrix. Followed by which, the author described the structure of the interviews and questionnaires that are to be used to observe the 'unknown variables': digital twin perception and (organizational) absorptive capacity. Lastly, the chapter concluded with an outline of the three-step data management process.

5

RESULTS

As the name suggests, this chapter presents the results of the semi-structured interviews and the targeted questionnaire designed in the previous chapter. The interviews explored the perception of digital twins in TSO/DSOs on the following elements: Awareness of digital twins, (potential) use-cases, motivation/factors of interest, stage of development, potential impact on current operations, risks, sector-wide challenges, suppliers, alignment with (organization) vision and implementation decision. Whereas, the questionnaire analyzed the absorptive capacity of TSO/DSOs when it comes to technology adoption.

The research methods primarily adopted in this chapter are: **Semi-structured interviews** and **Targeted questionnaires**

5.1. DIGITAL TWIN PERCEPTIONS

In this section, we present the findings of the interviews conducted with the energy market participants. As mentioned in the previous chapter, the interview consisted of ten central questions - hence, this section has also been divided into ten sub-sections, each of which compare the responses of participants around: Awareness of digital twins, potential use-cases, motivation/factors of interest, stage of development, potential impact on current operations, risks, sector-wide challenges, suppliers, vision of the organization and digital twins and implementation decision.

5.1.1. AWARENESS

Most participants were aware of the concept of digital twins, however, the level of awareness of digital twins varied across interviewees. A business consultant looking into digital twins at a **large-sized TSO/DSO with high budget-size and high grid-length** described digital twins as having four versions in increasing order of complexity: i) Visual Digital Twins, ii) Data collections (Data lakes) of the same physical asset, iii) Interactive digital twin models of assets and iv) Autonomous agents as Digital Twins. The visual digital twins are essentially 3D models of any physical assets and are the most popular in the industry right now. Digital twins as data collections on physical assets basically combine different data sources, locations and compile and centralize data in one place. Digital twins as interactive model of assets, allow interacting with the physical asset from a distance via the digital replica. Lastly, Digital twins as autonomous agents have the ability to act on behalf of a real thing/person/asset. This digital twin type gives every asset a real IP address and collects all the data that is available of this asset on that IP address and making this agent intelligent so that it could make its own conclusions on the available data. An enterprise architect at the same TSO/DSO believes that the granularity of a digital twin is an important aspect when defining digital twin - one can create a virtual node for every equipment on his/her network, which may lead to having too many nodes/digital twins or one can replicate the state of a sub-station as a digital twin rather than each and every small component.

The director at a **large-sized TSO/DSO with low budget-size and low grid-length** agreed the most part, with the definition of digital twins to be a digital replica of any physical asset. However, he makes a separation between the internal systems and the electricity network itself. At their firm, they are first looking at digital twins for their entire internal systems and then, consider the electricity grid. In essence, he sees digital twins as a simulation of the outside world, so judgement calls or decisions can be made remotely.

The innovation researcher of a **large-sized TSO/DSO with low budget-size and high grid-length** also defines a digital twin as a digital representative of assets on the field. They classify digital twins into two groups within their organization: Static and Dynamic. The static 3D model (twin) essentially allows one to walk around the grid and zoom-in/out, whereas the dynamic 3D model (yet to be deployed) allows for interaction with the physical object.

Whereas, the director at **Large-Sized TSO/DSO with high budget-size and low grid-length** argued that digital twins have been used as buzzwords as if they were something new. He stated that their grid models are a digital twin of the exact live situation of the grid and that they have been working with grid models since, computer-supported decision-making was possible. However, the novelty of digital twins arise in terms of using them non-synchronously to do maintenance work. The grid models that they currently use are not suitable to do maintenance work and a digital twin would essentially be a detailed enough model to help perform maintenance work, for instance, without having to visit the site upfront. In essence, he reiterates that a digital twin is novel for the maintenance world, whereas it has been around in the system operations world already. Furthermore, he argued that remote distance-steering of their physical assets has been already possible for a long time and is not new that a digital twin brings with it. In the 1980s, his organization started to build substations whose critical components could be monitored and steered from a distance.

Unlike the digital twin awareness levels, definitions and intricacies shared by other participants, the **small-sized TSO/DSO with high budget-size and high grid-length** simply agreed with the definition of a digital twin to be a virtual copy of a physical asset and did not provide any further insight into how they see/define digital twins internally within their organization.

A manager at an **energy supplier**, sees digital twins as a tool to solve challenges in district heating - their grids have delay factors and are influenced by external environmental conditions, which creates another layer of complexity. He stated that digital twins are essential a virtual representation of their asset base and systems, and allow for simulations under various conditions to get a better understanding of the their grid and how it functions as a whole.

5.1.2. POTENTIAL USE-CASES

Across all the interviewees, a central theme/use-case that most, if not all TSO/DSO echoed was predictive maintenance - the ability to predict when a given asset might breakdown before it actually does. **Large-sized TSO/DSO with low budget-size and low grid-length**, sees potential digital twin use-cases on the demand side both to forecast quality and capacity (demand) of electricity. They argue that every digital twin use-case for the energy sector, must ensure that three aspects are met: system balancing, system safety and system availability in order to minimize regret costs. Another digital twin use-case, they are looking into is timely asset replacement to base their investment decisions - a digital twin not only helps predict when asset replacement and investments might be required again, but also troubleshoot issues on the grid before the customer experiences them.

Manager at an **energy supplier** raised the fact that the first digital twin use-case that they worked on was a digital representation (simulation) of one of their heating grids. Prior to the grid simulations, the supplier would pump as much hot water as possible to ensure that they met the end consumer's temperature demand; However, due to certain delay factors, deterioration of the grid, ground temperature or bypasses in the system, they could not properly assess grid efficiency and performance. After having digital twins in place to simulate their heating grids, the supplier was able to lower the input heat temperature and reduce losses on the grid and still meet the end consumer's temperature demand - i.e., maximizing the utilization of the produced heat.

The **large-sized TSO/DSO with high budget-size and high grid-length** argues that the potential use cases depend on how a digital twin is defined. For instance, they conduct predictive analytics on their assets, but claim that it is not the same as having a digital twin. They believe that most digital twin use-cases are enablers to do achieve a certain objective. In their case, bringing together the state (data) of the grid, the connectivity data model and the physical assets allows them to exploit digital twin applications. Putting these three aspects together enables this TSO/DSO to create an 'Agent-based Digital Twin' to access all the relevant information of any given asset in a decentralized manner. They perceived this digital twin as an enabler as they required asset information to perform all other solutions such as: predictive asset management or calculating risks of outages on the grid. This TSO/DSO argues that they are convinced that most value in terms of use-cases like in the autonomous agent digital twins. They mention that one of the problems that the energy sector faces it that asset data is scattered in different locations/sources and is not available to everyone who needs it during the entire lifecycle of an asset – a digital twin can help solve this.

The **large-sized TSO/DSO with low budget-size and high grid-length**, sees demand forecasting and asset predictive maintenance as potential use-cases, but are not entirely sure of the specifics and mention that they require further research to be confident on whether these use-cases are feasible for their organization and its processes.

On the other hand, the **large-sized TSO/DSO with high budget-size and low grid-length** also affirms predictive maintenance to be a clear-cut use-case for their organization. Apart from predictive maintenance, they also believe secure supply is a use-case of interest. They explain secure-supply with an example - the speed of electricity is 200.000 km/s and the TSO/DSO can never be that quick even if they have all kinds of safety measures in place to prevent mishaps. Decisions where the human factor is critical to predict the outcome of secure supply, a digital-twin use-case is evident. Moreover, they are of the opinion that digital twin applications such as secure-supply and predictive maintenance might require substantial amount of capital investments, but they can be explained to the tariff payer as they are within his/her interest.

Small-sized TSO/DSO with high budget-size and high grid-length also affirms that predictive maintenance is a use-case to them. As a TSO/DSO, they are of the view that if digital twins can help forecast whether peak capacity demand is going to rise with real-time data, then they could enlarge the capacity earlier than expected rather than making estimations using generalized annual demand data. Hence, peak demand forecasting is an essential use-case that they'd like to see. Moreover, they prioritize having their assets running as optimally as possible at all times for as little costs as possible. In other words, if digital twins can assist them to match the demand and supply at all times, they can make better investment decisions. The TSO/DSO also mentions that as of now, they have not implemented any digital twin or its use-cases, but have made data lakes to gather more data/knowledge of our assets as they have limited resources with respect to labor and capital for fully-functioning digital twin use-cases.

5.1.3. MOTIVATION/DRIVERS OF INTEREST

The **large-sized TSO/DSO with low budget-size and low grid-length** believes operational efficiency and market transparency to be a couple of reasons that draw their interest to digital twins. They are of the view that: initially, digitalization projects like digital twins used to only have internal drivers such as improving productivity and efficiency in investment decisions and/or maintenance plans; but now, external drivers such as legislation, obligations from regulators (e.g.: sustainability) and customer/stakeholder demands play a much more important role to drive digital twin adoption.

On the contrary, the **large-sized TSO/DSO with high budget-size and high grid-length**, does not perceive customer demands and regulations as the main factors that sparked their interest. They believe there are three aspects that caused them to consider digital twins: field-worker perspective, engineer's perspective and the simulation perspective. As a field-worker, one needs to be aware of the grid environment/complexities even before going onsite. Second, an engineer must have the most actual image of the grid environment. Third, from a simulation perspective, one could calculate current flow and simulate how the grid behaves if a transformer fails, for instance - all these three factors are promised by digital twins. In addition, they describe that digital twins completely solve the problem of finding all the data associated with an object and with AI and machine learning, they could send an alert when an incident of the past occurs again in the future.

The **energy supplier**, is of the view that the drivers of digital twin adoption are both financial and sustainability-related. One of their missions is to speed-up the energy transition and make the energy transition for everyone - to do so, they claim to have to maximize the use of the heat that they produce. However, they believe that this may not be the most incredible business case, but they do see digital twins delivering value on the sustainability front and save operational costs as digital twins promise to make their grid more efficient.

The **large-sized TSO/DSO with low budget-size and high grid-length**, finds digital twins to be of interest due to their promising applications in simulation (e.g.: how the grid functions) and training (e.g.: training staff on how to operate an asset). They are investigating what the possibilities of digital twins in these applications are. They also regard operational benefits of digital twins to be an interesting factor: 'if digital twins can link information to a physical asset and easily acquire that information to the field, that would have operational benefits for us'.

The **large-sized TSO/DSO with high budget-size and low grid-length** sees digital twins supporting one of their core values of secure supply with having as little downtime as possible and believes a digital twin supports them to do so. With a digital twin, they would have the ability to react almost instantaneously 24/7 in case an incident occurred onsite.

The **small-sized TSO/DSO with high budget-size and high grid-length** have the opinion that savings in costs, capacity, time-hours and human resources are drivers towards digital twins. Having digital twins of their assets, they argue would reduce the number of (maintenance) inspections required to keep the asset running and reduce untimely asset breakdowns. This would enable the TSO/DSO to save money; more importantly save capacity, people and time hours as they face a shortage of specialists at the moment. In a certain sense, the TSO/DSO can both utilize their specialists in the most optimal way and make better decisions, cheaper and quicker by having more knowledge/data on their assets - all thanks to digital twins. They are also of the view that the main driver to optimize asset maintenance and replacement decisions is monetary – one can optimize the amount spent.

5.1.4. DEVELOPMENT STAGE

The **large-sized TSO/DSO with low budget-size and low grid-length**, mentioned that they are in the pilot phase. They have a system in place that describes the current state of their grids and/or assets and whether one needs to take any action. A digital twin is more about modelling and predicting asset behavior in the future (5 or 10 years)- this is something that they do not have in place yet. The first pilot project at their organization started about 3 years ago during a time when they observed a lot of congestion on their network, and they wanted to proactively add more capacity to the network as and when needed.

The **energy supplier**, on the contrary, expressed that they have a digital twin running full-time in their operations and not just pilots. They explained further, that to get an better understanding of their grid at every moment, they have a digital twin in place which receives data from continual measurements at the production site, distribution station and at consumers via smart meters. They believe, the more important question is how rich is the digital twins in terms of data processed rather than if if a TSO/DSO has a digital twin or not. They are of the view to not have uncovered all the digital twin use-cases in the organization yet.

On a scale of 1 to 10, the **large-sized TSO/DSO with high budget-size and high grid-length** considers themselves to be at 1.5, even though they have conducted several pilot projects already. In their view, this is because there are many opportunities to uncover. Furthermore, they point out that as a business, they have stopped the digital twin initiative for now (started in 2017 at the HV network), but, they still have a few use-cases around digital twins (simulations and predictive analytics) at a smaller scale. The failed deployment of the digital twin concept within their organization was due to the fact that the proposal had been rejected by their management team. The rejection was on the grounds of misalignment of expectations within the organization between: asset-owners and service-providers. The service-providers mainly perform provisioning and grid maintenance, hence, they are concerned only with the (digital twin) use-case of: field management ('I must send my engineer to the field, and they have to know servicing'). On the other hand, the asset-owners wanted to know more about their asset portfolio and its behavior (state) under different conditions. From an asset-owner perspective, the whole network is connected: so everything in the grid is one and should be connected to a digital twin. Whereas, from a service-provider perspective, there is only a certain part that needs servicing and is relevant for a digital twin. Therefore, asset-owners wanted a digital twin for the entire grid (e.g.: to perform connectivity calculations) and service providers wanted digital twins for fragmented parts of the network – there was no common ground to develop a digital twin, mainly from a use-case perspective. Furthermore, they explained, that other productivity challenges arose: they had too few people to realize the digital twin perspectives of asset owners. Hence, the initiative has been sidelined, but is still running within their organization at a very small scale within IT, but not from a business perspective.

The **large-sized TSO/DSO with low budget-size and high grid-length**, has already conducted projects related to digital twin research, but none for implementing digital twins so far. The innovation officer, believes that they are still in the initial research phase - on a scale of 1 to 10, she claims to be at 3 in the development of a digital twin. The first time, she heard about digital twins was one and a half years ago from a colleague of mine when she started with her current role.

The **large-sized TSO/DSO with high budget-size and low grid-length** has also conducted digital twin pilot projects within their organization. They have had digital twins for some of their offshore platforms and for their maintenance work. Apart from pilots, the head of asset data management describes four steps successful digital twin deployment:

- **Step-1:** Prepare your company structures
- **Step-2:** Setup standards for (uniform) digital twin creation
- **Step-3:** Produce/Implement Digital Twins
- **Step-4:** Work with Digital Twins

This TSO/DSO believes to be currently at step-1. They are laying the foundation by aligning data architectures, item designations and other agreements not only within the company but also with suppliers and the entire value chain. They are of the view that digital twins would be practical only if all the different vendors offer (uniform) standardized digital twins, which are based on the standards on the system operators. The participant stated that, he first of the buzzword 'digital twin' in 2018 and the offshore pilot project at their organization started in 2019. Back then, he explained, it was difficult to find vendors who could deliver data structures as per their standards (ISO19650) and also allowed the use of linked data to share these data structures with other suppliers.

The **small-sized TSO/DSO with high budget-size and high grid-length**, claims to not be at 1 on a scale of 1 to 10. They have been busy with the digital twin concept by talking to industry experts and academics to look into the possibilities. The first time, the director heard about digital twins was in 2019 from a professor who wrote a book on the technology. Specifically for digital twins, this TSO/DSO has not conducted any pilot projects solely due to limited resources in people and capital. Hence, for now they have only developed data lakes (collection of asset data), but not digital twins.

5.1.5. POTENTIAL IMPACT ON CURRENT OPERATIONS

The **large-sized TSO/DSO with low budget-size and low grid-length** expresses difficulty to generalize the impact of digital twins in hard numbers. They argue that, in some use-cases, digital twin could reduce the total cost of ownership by 10-20%, and while in others they see no significant impact. Nonetheless, they believe digital twin pilots have had significant benefits in their risk planning and asset maintenance - but at the moment, they cannot generalize the impact to every use-case out there.

From the perspective of the **energy supplier**, they have had to do several pilot projects to have the digital twin fully operational since about a year. They are evaluating the impact and are still considering which model to further pursue (they have two models from two different providers). Initially, employees in their organization did not call it a digital twin, but rather a simulation and/or optimization tool depending ton the use-case at hand.

Based on the pilot projects conducted in the past, the **large-sized TSO/DSO with high budget-size and high grid-length**, is of the view that digital twins increase hands-on time and productivity of their employees. For instance, maintenance engineers could solely focus on their field tasks as the administrative tasks such as collecting asset information from SCADA systems or work order history were assigned to the digital twin. In other words, they perceived the impact of digital twin pilots mostly in the automation of existing processes within their organization.

The **large-sized TSO/DSO with low budget-size and high grid-length**, also expects digital twins to boost worker productivity - 'If there's a blackout, workers can already find where the problem is and know how to fix it before visiting the site'. Moreover, they also believe that administrative tasks like collecting asset data, finding assets and knowing their state would become much easier.

The **large-sized TSO/DSO with high budget-size and low grid-length**, express criticism on the impacts of digital twins on their operations so far ('a good play tool'). The head of data asset management believes, on a company level, digital twins do not add any value unless they are scaled-up and standardized across the industry. They are of the opinion that scalability is key - For instance, if a TSO/DSO has deployed 100 digital twins and if they are not/cannot be standardized and scaled, then it could potentially be expensive to store and maintain all these different data structures.

The **small-sized TSO/DSO with high budget-size and high grid-length** expects two main (potential) impacts of digital twins. Firstly, at the moment, it takes a lot of time and energy for them predict how the energy transition will influence their assets - with digital twins, they could run scenarios over and over again, taking much lesser time. Secondly, as a TSO/DSO, they acknowledge that they are behind other TSO/DSOs when it comes to digitalization projects like the digital twin because they own older assets and have shortages in human resources. They expect digital twins to make them more flexible and proactive as they would be able to predict customer demand more efficiently with lesser resources; whereas now, they are reactive to customer demand and always trying to match their supply with the demand.

5.1.6. RISKS

When looking at risks, the **large-sized TSO/DSO with low budget-size and low grid-length**, does not consider data security and privacy as one of the current risks, however as adoption increases, this risk could be eminent in the future. At present, the only risk they perceive is not deploying digital twins as it may affect their license to operate given the adoption is for the most externally-driven by legislation.

The district heat **energy supplier** sees limited technical know-how as a risk: 'Digital twins require an in-depth understanding of the grid itself. There are only a handful of people who understand how it works'. They reiterate that technical knowledge of the grid and digital twins are key aspects both within the organization and at the vendor. They see data security and privacy as a predictable risk with any digitalization project (not just specific to digital twins) and believe they are mitigable if the right security standards are followed.

For the **large-sized TSO/DSO with high budget-size and high grid-length**, the risk is lack of digital twin technical knowledge within the organization: 'People did not understand the concept of digital twins and what it meant for them'. The lack of knowledge is a current risk that they observed in their pilot projects. They believe digital twins are a long-term investment, hence internal knowledge ought to improve over the long-term. The business consultant, does not consider data security as a huge risk - he mentions, 'data security completely depends on how you design your digital twin in the first place and whether you have the right measures'. A technical risk that he sees is the existence of false positive/negatives when using machine learning (ML) algorithms in digital twins. He argues, if the models draw a conclusion based on a false positive/negative that could be dangerous for functioning of the grid - this risk, he believes are mitigable by training the digital twin (ML algorithm) with different data sets.

The **large-sized TSO/DSO with low budget and high grid-length**, sees data security as a potential risk of digital twins which, they believe is amplified if all the data is centralized. However, they do not see data privacy as a major risk, as there is sufficient regulation in the energy sector that safeguards the privacy rights of end consumers. Moreover, the innovation officer explains that (consumer) data privacy in a priority within their organization, hence, they'd not consider deploying digital twin that do not take into account privacy regulation. In other words, privacy risk does not seem relevant from their perspective. Another risk that, they consider relevant is over-reliance on digital twins - if engineers are solely reliant on the digital twin and for whatever reason the data quality was compromised, then this could have severe consequences for their grid.

Likewise, the **large-sized TSO/DSO with high budget-size and low grid-length** also sees over-dependence on digital twins as a risk. However, they see limited risk of data leaks/privacy claiming that if digital twins are designed as per architectural rules such as ISO27000, this risk is mitigated. Another risk they take into account is limited scoping and use-case awareness. If the digital twin has been designed for actual steering on the network, then it ought to be extremely accurate relative to digital twins designed to assist in maintenance work - these twins cannot be interchanged.

Alike other TSO/DSOs, the **small-sized TSO/DSO with high budget-size and high grid-length**, also does not perceive cyber-security as a major threat given strong regulations in the sector and citing that their OT (Operational Technology) network is highly secure and is audited regularly. In their view, like many other TSO/DSOs, the highest risk is becoming overdependent on digital twins, so much so that engineers never go into the field to inspect assets - which would be a major concern if compromises to data quality occurred.

5.1.7. SECTOR-WIDE CHALLENGES

When it comes to digital twin adoption challenges faced by the energy sector, the **large-sized TSO/DSO with low budget-size and low grid-length**, believes ensuring system balance, system security and system availability are challenges not only relevant to them as a TSO/DSO, but to the entire sector. In their view, the objective of the energy market is decentralizing the system and introducing new form of energy (e.g., heat or hydrogen), but at the same time, energy market participants must ensure to keep the networks safe, secure and in balance. Moreover, they advise smaller DSOs who have limited resources to work together with other market participants and the TSO. Digital twins, from their perspective, are not only regionally relevant, but also have national importance as they bring the potential to help balance electricity networks more efficiently.

On the contrary, the major Dutch heat **energy supplier**, considers investment costs to be a major challenge especially for the smaller players in the energy market. The manager smart grid & innovation, stated that their organization is convinced that the future of energy is going to be across mediums and go forward and backward. For instance, in the future, more consumers will be able produce energy and deliver it back to the grid if in excess. As energy suppliers, they are expected to make much more operational decisions on a daily basis than today - which is expected to be complex and cannot be left to individuals alone. He reiterates his stance on digital twins by claiming that companies which have sufficient resources to make investments in digital twins are the ones that will survive the future.

The architect at the **large-sized TSO/DSO with high budget-size and high grid-length**, is of the view that leadership/management teams of many, if not all utility companies including electrical, logistics and infrastructure have limited understanding of the capabilities of a digital twin. There is a disconnect between the technical and the business perspective. From a technical perspective, the challenge, this TSO/DSO believes, is reaching an industry-wide consensus on standards such as: object naming conventions, codes and (asset) data sharing between companies. From a business perspective, however, most companies fear sharing (asset) data with other TSO/DSOs due to uncertainty around what the other TSO/DSOs could do with their data, i.e., conflicting business models. The only manner to solve this challenge, the business consultant, claims is by redesigning business models that foster digital twin adoption and embrace energy transition.

The innovation researcher at a **large-sized TSO/DSO with low budget-size and high grid-length**, is of the view that high investment costs may be a challenge for later. For now, she describes, a bigger challenge is the problem of scoping. Specifically, at which level of detail does a TSO/DSO benefit from having a digital twin ('are digital twins of screws in the asset necessary or would a larger component suffice?'). At this stage, she would be unable to point towards how much investment costs could be, but states that they would depend on the scale and could become a barrier for some DSOs. A second challenge (as with any digital technology) is culture – if a TSO/DSO deploys a digital twin, the organization should also account for employees (sentiments) reactions and whether it meets expectations.

The **large-sized TSO/DSO with high budget-size and low grid-length**, is of the view that the central challenge is regulation. The head of asset data management argues that the regulator is not prepared for digitalizing TSOs and DSOs, as digital twins are not capital expenditures, but operational expenditures - and operational expenditures are what regulators want to prevent. He also believes that making a digital twin business case for offshore activities is easy - as flying employees onsite puts lives at risk and is expensive. On the flip-side, making a business case for onshore substations is harder as TSO/DSOs often question the value of digital twins when compared to their investment - as workers can directly visit onshore substations by car to do maintenance work and there is no need for 24/7 availability.

From the **small-sized TSO/DSO with high budget-size and high grid-length's** perspective, the main challenge for the energy sector only comes after the large-scale digital twin adoption. He portrayed concern over the fact that if digital twin suppliers would have information/data of the assets on the grid, they could potentially takeover the jobs of smaller DSOs on the promise of taking care of the entire Dutch electricity grid and tackle issues like congestion, load balancing at a cheaper cost in a more efficient and reliable way.

5.1.8. DIGITAL TWIN VENDORS

Looking at the **large-sized TSO/DSO with low budget-size and low grid-length**: For their initial pilots, they built an IT architecture in-house and classified them into two: Operational digital twin and Strategic digital twin. The director stated that they are planning to roll-out and implement the entire chosen architecture within the next 2-3 years. He emphasized the point that defining a digital twin is important - one, could also argue that the TSO/DSO already has some kind of a digital twin with their GIS (Geographical Information System). However, the director, believes that a digital twin has much more to offer: it is dynamic and with the right data inputs, digital twins can provide more insights which can be used to model and/or forecast conditions, in turn, helping make critical business decisions.

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The district heat **energy supplier**, on the other hand, had a unique experience when compared to TSO/DSOs around digital twin vendors. The manager, contends that two digital twin vendors approached them rather the other way around. He argues that the vendors approached them and showed the value of their digital twins and it was not something that their organization initiated. The participant refrained from taking their names, but did state that the vendors developed digital twins specifically for the district heating market and cannot be applied to other markets.

The **large-sized TSO/DSO with high budget-size and high grid-length** have already done a couple of sessions with IBM and Bentley systems. However, they are of the view that the offerings provided by these vendors did not match their ambitions/challenges. As an example the business architect stated that, one of the features that they wanted on their digital twins was the ability to combine certain aspects of IoT, open data and node inter-connectivity in order to have an 'open-source digital twin'. In the end, the TSO/DSO organized their own innovation track internally and did not place any orders from the vendors. This TSO/DSO also stated that one must be aware of vendor bias, in the words of the business consultant: 'the large software companies try to lock you in their software, so you have to also purchase their next software suite'.

The innovation researcher of the **large-sized TSO/DSO with low budget-size and high grid-length** reasoned that she is unaware of digital twin vendors due to the sole reason that they are still in the initial research phase. In the later stages, if she had to make the choice between developing a digital twin in-house or externally via vendors, she urges that she would first take the advice of her (data) security colleagues.

Whereas, the **large-sized TSO/DSO with high budget-size and low grid-length** has been in contact with ABB and IBM for developing digital twins for their existing assets. The TSO/DSO claims that they need to figure out how to develop digital twins on existing assets that have a lifespan of 20 to 60 years as there is so much legacy data associated with these assets that no contractor or vendor has been able to assist them so far. For new physical assets that are yet to be tendered, they look for external contractors that can deliver a digital twin according to the their (data) standards along with the (new) physical asset. The head of asset management also argues that when it comes to digital twins of each individual assets, they consider multiple vendors because being a state-owned company they must abide by EU tender rules.

The **small-sized TSO/DSO with high budget-size and high grid-length** describes that they have spoken to smaller vendors that produce GIS systems (for their data lakes), but they have not contacted any vendors that provide digital twins. The TSO/DSO maintains that they are still in the research phase and have not arrived the phase to contact suppliers yet.

5.1.9. VISION OF ORGANIZATION & DIGITAL TWINS

The **energy supplier**, envisions decentralizing power and ensuring that everyone can participate in the energy transition. They are of the view that Digital twins are key to help them achieve their vision. They believe that if an organization does not consider deploying digital twins, then it cannot exploit all the benefits from the already scare sustainable power. In their opinion, the challenge now and going forward will be managing sustainable energy and optimization methods such as digital twins are going to be key to combat this challenge. Lastly, the energy supplier believes that in the future, the term digital twins will be more specific unlike at present, and that digital twins will be deployed more easily as the value of sensors, data transportation and telecom costs are going to go down. To conclude, the are convinced that digital twins are going to be ubiquitous across the energy landscape.

The **large-sized TSO/DSO with high budget-size and high grid-length** does not foresee the large-scale digital twin adoption in the next 3-5 years for their organization. They are of the view that digital twins will remain in the background for the coming years at their organization as their current focus is on making production plans, meeting capacity targets and extending their electricity network and digital twins do not necessarily provide assistance on these objectives. Put simply, Digital twins will remain on the side-track at this TSO/DSO for a couple of years as their focus has shifted to more urgent business-related issues rather than developing and deploying emerging technologies like digital twins. Furthermore, the board of management at this TSO/DSO is not clear if they even need a digital twin as the discussions are so complex given the involvement of several stakeholders.

The **large-sized TSO/DSO with low budget-size and high grid-length** is of the view that not the entire Dutch energy sector will adopt digital twins in the next 5-10 years, but most TSO/DSOs will. The vision of this TSO/DSO is to be able to deliver energy to their clients in a more optimized way and, if digital twins help them do so, then they certainly align with their vision.

The **large-sized TSO/DSO with high budget-size and low grid-length** believes that digital twins will widely be adopted in their offshore and onshore activities with a timeline of at least another 10 years before full integration as digitalization is not only about implementation but also culture change. The vision of this TSO/DSO on digitalization is that it ought to be an enabler to tackle their current and future challenges that come with the enormous growth of new forms of energy- offshore wind farms and onshore PV farms and lesser dependence on gas among others. They are of the opinion that, digitalization initiatives like digital twins align with their vision and thus, they must consider more investments in such projects.

The **small-sized TSO/DSO with high budget-size and high grid-length** believe that digital twins will fully be integrated into their operations only 10 years from now. Due to limited resources and smaller size relative to other TSO/DSOs, this TSO/DSO finds it rather challenging to already build towards digital twin systems. As an alternate, in the coming years, they are considering more investments in methods like data lakes to better utilize the data which they already collect from their physical assets. Furthermore, they foresee that the adoption of digital twins will cause a push for uniformity across the Dutch energy sector and regulators are already demanding transparency and uniformity on aspects like maintenance procedures, quality checks and investment practices from TSO/DSOs.

5.1.10. IMPLEMENTATION DECISION

Of the participants to whom the question, whether they would implement a digital twin in their organization today if they decision was solely in their hand, was put, mixed responses were received. The energy supplier was the most positive, so much so that they claim: 'without digital twins achieving the energy transition would not be possible'.
The **large-sized TSO/DSO with high budget-size and low grid-length** was also positive, but was conscious about the time required to fully integrate digital twins in operations (about 10 years). Whereas, the **large-sized TSO/DSO with low budget-size and high grid-length** may consider implementing digital twins after their research efforts and if and only if the digital twin being offered is secure and does not face privacy-related challenges. On the contrary, the **small-sized TSO/DSO with high budget-size and high grid-length** seemed to not be entirely convinced of the proposition due to the potentially high investments and resources required.
Finally, the **large-sized TSO/DSO with high budget-size and high grid-length** would not take this decision today, as their proposal has already been declined by their management team in the past due to misalignment in expectations between internal groups within the organization - they further, claimed that digital twins are not a business priority right now and that their organization might not be ready for them at present.

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5.2. SUMMARIZED INTERVIEW FINDINGS

The perception of digital twins as experienced by Dutch TSO/DSO was analyzed in ten attributes: Awareness levels, Potential Use-cases, Motivation/Factors of Interest, Development stage, Potential impacts, Risks, Sector-wide challenges, Vendors, Vision and Implementation decision.

- **Awareness levels**: When looking at Digital Twin Awareness, almost all interviewees discussed some sort of (internal) classification of how they categorize digital twins within their respective organization. This suggests that most TSO/DSOs have a good understanding of digital twins from a theoretical perspective except for the small-sized TSO/DSO with high budget-size and high grid-length, who only agreed to the interviewer's definition of a digital twin and did not provide any further insight into how they view digital twins at their firm.

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- **Potential Use-cases**: Across all TSO/DSOs, the recurring digital twin use-cases of interest were predictive maintenance and demand forecasting. The interest in these use-cases is related to the ongoing challenges that are brought by the energy transition such as untimely asset breakdowns, shift to renewable sources of energy and increased unpredictability in energy demand among others.

- **Motivation/Factors of Interest**: When it comes to factors of interest/motivation to pursue digital twin initiatives, most TSO/DSOs viewed internal drivers such as operational efficiency, reduction in asset down-time, employee training, simulation, cost savings, and alignment with core values to be more prominent than external drivers. Having said that, the large-sized TSO/DSO with low budget-size and low grid-length views external drivers such as: regulatory pressures, customer expectations, and market transparency to be primary drivers of their interest in digital twins.

- **Development stage**: The interview responses suggest that Dutch TSO/DSOs are to be found across the spectrum of digital twin development stages. Large-sized TSO/DSO with low budget-size and high grid-length are in the initial research phase, whereas small-sized TSO/DSO with high budget-size and high grid-length are also in the research phase, but are skeptical of deploying pilots due to limited resources (both human & capital) at hand. All other TSO/DSOs are in the pilot phase and have already experienced digital twin pilot initiatives within their organizations.

- **Potential impacts**: The (potential) impact of digital twins at TSO/DSOs so far has been diverse. Some interviewees suggest that they expect to see boosts in worker productivity as digital twin help automate administrative tasks that are performed within the organization, in turn, increasing worker hands-on time. Others are of the view that given the current levels of adoption, it is too early to generalize the impacts of digital twins on their processes. Whereas, some TSO/DSOs expect digital twins to help them be more flexible to manage changing consumer energy demands. Having said that, the large-sized TSO/DSO with high budget-size and low grid-length is of the view that digital twins will not add significant value to their operations unless they are standardized across the energy sector.

- **Risks**: When analyzing the potential risks of digital twins, a clear trend across the industry was found. All interviewees are of the view that there are limited to no significant risks to data security or privacy with the adoption of digital twins at this stage. If there exist risks to data security or privacy, they are minimal and are easily mitigable by simply abiding by the (stringent) data privacy/security laws that are currently in place in the Dutch energy sector. On the other hand, over-reliance or trust in digital twins was a common risk perceived by many participants.

- **Sector-wide challenges**: The interviews suggest quite a wide variety of challenges that the energy sector faces around the adoption of digital twins. Firstly, organizations can find it challenging to limit the scope of digital twins i.e, digital twins are not universal; based on the application/use-case it is essential to recognize the level of accuracy a digital twin needs (e.g.: down to the component level of part level). For instance, in applications like asset-steering more accuracy might required relative to predictive maintenance. In addition, smaller TSO/DSOs may face higher obstacles when it comes to digital twins due to limited resources at the hand, it is recommended to work together with other TSO/DSOs at the national level. Another challenge, some TSO/DSOs view is limited understanding of digital twins in management teams and some believe regulators avoid conversations around digital twins as they are an operational expenditure for them and not a capital expenditure. To take it a bit farther, a TSO/DSO suggested that if digital twins are adopted at a large-scale, they are concerned of losing business to the vendors of digital twins in the future.

- **Vendors**: In all, the awareness of digital twin vendors at TSO/DSOs was mixed. The large-sized TSO/DSO with low budget-size and low grid-length had limited awareness of digital twin vendors as they developed digital twins internally for their pilot initiatives. Similarly, the large-sized TSO/DSO with low budget-size and high grid-length and the small-sized TSO/DSO with high budget-size and high grid-length were also unaware of digital twin vendors, although the reason being that they were still in the initial research phase. However, other TSO/DSOs were aware and have been in touch with both international digital twin vendors and smaller vendors at the national level.

- **Vision**: TSO/DSOs, in general, are of the view that the full integration of digital twins in operations will take at least 10 years some reasons being culture change, limited (capital) resources, uncertainties in benefits/risks and restricted knowledge in management teams among others. All TSO/DSOs believe that digital twins align with their vision in some manner or the other and help tackle challenges brought by digitalization and the energy transition.

- **Implementation decision**: Overall, there were mixed reactions on the decision to implement and fully integrate digital twins in operations today given the existing knowledge and resources available within TSO/DSOs. The energy supplier was exceedingly positive, the large-sized TSO/DSO with high budget-size and low grid-length remained optimistic but conscious about time required to fully adopt. On the contrary, the large-sized TSO/DSO with low budget-size and high grid-length would only adopt if the risks were extensively investigated. Other TSO/DSOs remained pessimistic on fully-integrating digital twins into their operations today.

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5.3. ORGANIZATIONAL ABSORPTIVE CAPACITY

This section presents the outcomes of the questionnaire which measures the organization's absorptive capacity and the level of digital twin adoption. As mentioned in section-4.4, Flatten et. al measures organizational absorptive capacity on four well-defined attributes: Acquisition, Assimilation, Transformation and Exploitation. An organization is considered to have a high absorptive capacity in a given dimension (Acquisition, Assimilation, Transformation or Exploitation), if the respondent(s) marks Somewhat Agree or Strongly Agree in the majority of the statements in the respective (dimension) block. As

shown in figure-5.1, there were 7 questionnaire respondents: two from the Large-sized TSO/DSO with high-budget size and high grid-length, one from the energy supplier and one from each of the remaining 4 organizations. The results of the absorptive capacity of the organizations based on the questionnaire responses have been summarized in figure-5.1.
When looking at the dimensions of **Acquisition** and **Exploitation**: the responses suggest that all the organizations have **high (Acquisition) absorptive capacity** and **(Exploitation) absorptive capacity** regardless of their organizational size, net profit or the length of circuits they manage.
On the other hand, when it comes to the dimension of **Assimilation**, the responses suggest a mixed picture. Large-sized TSO/DSO with high budget-size and low grid-length, Large-sized TSO/DSO with high budget-size and high grid-length and Small-sized TSO/DSO with high budget-size and high grid-length, portray **low (Assimilation) absorptive capacity**. Whereas, the other organizations portray **high (Assimilation) absorptive capacity**. Similarly, apart from the Large-sized TSO/DSO with high budget-size and high grid-length all other organizations portray **high (Transformation) absorptive capacity**.

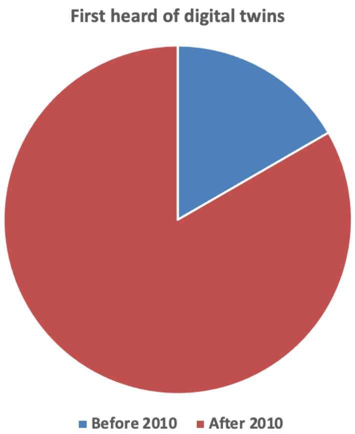
Overall, the Large-sized TSO/DSO with high budget-size and high grid-length has the lowest Absorptive Capacity as per the questionnaire responses. This finding could potentially be related to a finding from the interviews. During the interview, this TSO/DSO stated that they have had several pilot projects, but their management team decided to reject the adoption of digital twins into operations for now on the grounds of internal conflicting expectations and not being a business priority. However, this does not imply that the lower absorptive capacity led to rejection of the digital twin proposal. The relationship between the (suggested) low absorptive capacity and rejection of the digital twin proposal at this TSO/DSO requires to be further investigated to make any additional claims. All the other organizations exhibit high levels of absorptive capacity irrespective of their organizational size, net profit or circuit length. Put simply, the trend: large-sized TSO/DSOs have low (Assimilation) Absorptive capacity was not found. As a final note, the absorptive capacity of the Small-sized TSO/DSO with high budget-size and high grid-length is inconclusive as the respondent decided to or did not fill-in the entire questionnaire.

Apart from the absorptive capacity results, the questionnaire also established findings around the following aspects: (First) Source of Awareness/Interaction point, Decision to implement Digital Twins, Adoption Barriers and Budget Allocations.

- **(First) Source of Awareness/Interaction point:** As depicted in figure-5.2, 83% of the TSO/DSOs heard about the concept of digital twins also after 2010. Whereas 17% were aware of the concept before 2010. The year 2010 is considered a milestone in the digital twin adoption as the first practical definition of a digital twin was defined by NASA in an application to improve their physical model simulation of spacecrafts in 2010. 67% of TSO/DSOs reported to first hear about digital twins from sources of information that are external to their organization namely: suppliers, conferences, research papers and the Gartner Hype Cycle. On the other hand, 33% of TSO/DSOs first heard about digital twins from internal sources: colleagues and internal presentations.

	Organizational Absorptive Capacity			
TSO/DSO	**Acquisition**	**Assimilation**	**Transformation**	**Exploitation**
Large-sized TSO/DSO with low budget-size and low grid-length	Overall: ***High*** • Strongly agree (3/3)	Overall: ***High*** • Strongly agree (1/4) • Somewhat agree (2/4) • Somewhat disagree (1/4)	Overall: ***High*** • Strongly agree (3/4) • Somewhat agree (1/4)	Overall: ***High*** • Somewhat agree (2/3) • Strongly agree (1/3)
Large-sized TSO/DSO with low budget-size and high grid-length	Overall: ***High*** • Somewhat agree (3/3)	Overall: ***High*** • Somewhat agree (4/4)	Overall: ***High*** • Somewhat agree (4/4)	Overall: ***High*** • Somewhat agree (3/3)
Large-Sized TSO/DSO with high budget-size and low grid-length	Overall: ***High*** • Somewhat agree (2/3) • Somewhat disagree (1/3)	Overall: ***Low*** • Neither (3/4) • Somewhat agree (1/4)	Overall: ***High*** • Somewhat agree (4/4)	Overall: ***High*** • Somewhat agree (3/3)
Large-sized TSO/DSO with high budget-size and high grid-length *(2 respondents)*	Overall: ***High*** • Somewhat agree (4/6)	Overall: ***Low*** • Somewhat agree (3/8) • Somewhat disagree (4/8) • Strongly disagree (1/8)	Overall: ***Low*** • Somewhat agree (4/8) • Somewhat disagree (4/8)	Overall: ***High*** • Somewhat agree (4/6) • Strongly agree (1/6) • Neither (1/6)
Small-sized TSO/DSO with high budget-size and high grid-length	Overall: ***High*** • Somewhat agree (3/3)	Overall: ***Low*** • Neither (3/4) • Somewhat disagree (1/4)	-	-
Energy Supplier	Overall: ***High*** • Somewhat agree (1/3) • Strongly agree (2/3)	Overall: ***High*** • Somewhat agree (3/4) • Neither (1/4)	Overall: ***High*** • Somewhat agree (3/4) • Strongly agree (1/4)	Overall: ***High*** • Somewhat agree (2/3) • Strongly agree (1/3)

Figure 5.1: Organizational Absorptive Capacity (TSO/DSO)



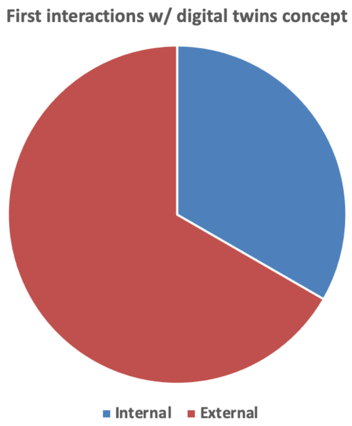


Figure 5.2: First heard of digital twins (left); Source (right)

- **Decision to implement Digital Twins:** Figure-5.3, suggests that only 67% of technology adoption decision-makers would take the decision to fully deploy digital twins into their operations given their existing technology, resources and knowledge levels. Whereas, 17% propose that more research into the risks and benefits is required before they could make their decision. Just as in the interviews, the decision to fully implement digital twins in existing operations today remains mixed.

- **Adoption Barriers:** Figure-5.4 suggests that, at present, there is no 'single' attribute that is considered as a barrier by all the TSO/DSOs in the Netherlands. From the responses, it was found that there are many differing opinions when it comes to digital twin barriers and that there are several barriers to the adoption of digital twins in the Dutch energy sector. Of all the responses, complexity of digital twins was considered to be a significant barrier. Followed by, high investment costs, uncertainty around added value, compatibility with existing technologies & ways-of-working and limited knowledge within the organization. Large-sized TSO/DSO with low budget-size and high grid-length considers uncertainty in risks, uncertainly in benefits and complexity as significant barriers. The selection of these barriers by this TSO/DSO is to some extent related to the fact that they are still in the research phase and did not conduct any pilots as such (as mentioned during the interview). Other barriers to adoption mentioned on the questionnaire responses include: limited availability of high quality data to develop digital twins, conflicting business models when sharing data outside company and reluctance of software vendors to decentralise data.

- **Budget Allocations:** All the TSO/DSO in the Netherlands that took part in the research have budget allocation towards digitalization projects and budgets specifically catered to digital twins irrespective of their organizational size, net profit or the circuit length.

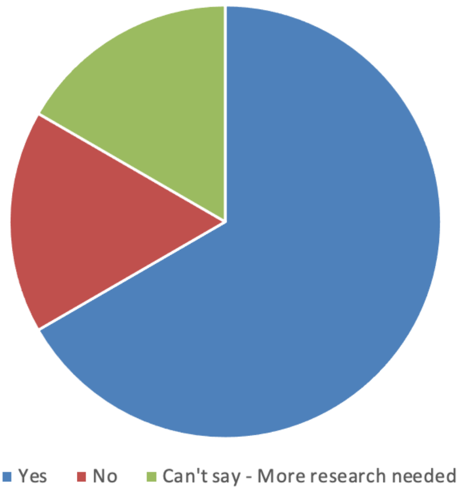


Figure 5.3: Decision to deploy digital twins with existing knowledge and resources

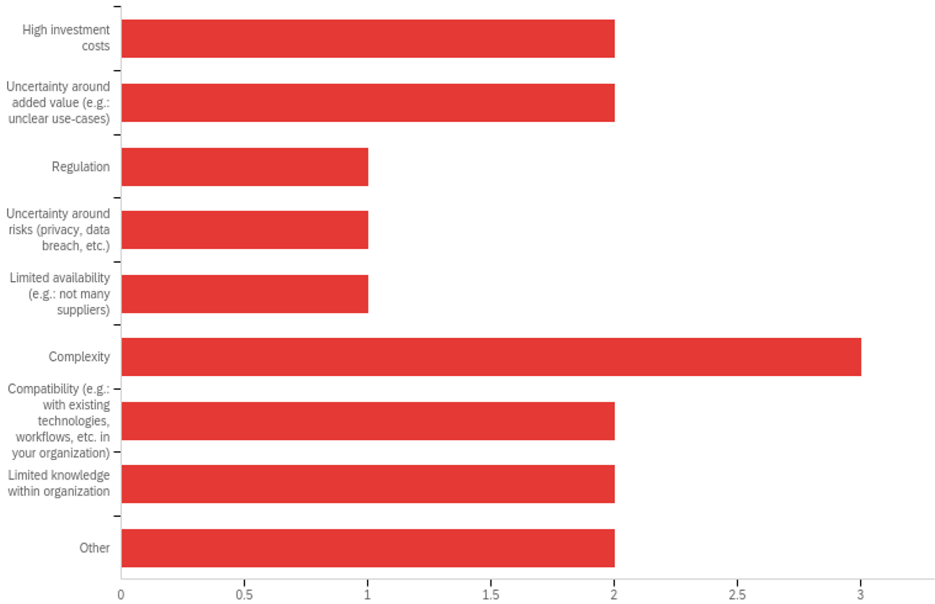


Figure 5.4: Barriers to the adoption of Digital Twins

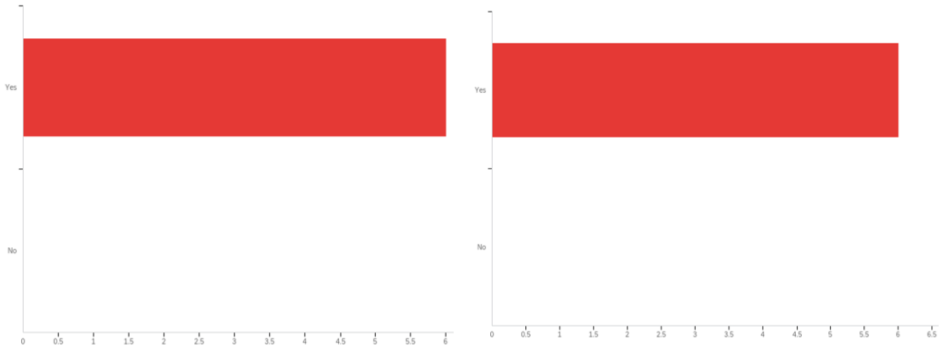


Figure 5.5: Budget allocation towards Digitization projects (left);
Budget allocation specifically for digital twins (right)

5.4. CONCLUSION

This chapter uncovered the current perception of digital twins as experienced by Dutch TSO/DSOs. The perceptions of digital twins were analyzed by conducting (semi-structured) interviews with technology adoption decision-makers within the Dutch TSO/DSOs. As shown in figure-6.1 and figure-6.2 in the appendix, a total of eight interviews with six TSO/DSOs were conducted with each interview covering ten perspectives: Awareness levels, Potential Use-cases, Motivation/Factors of Interest, Development stage, Potential impacts, Risks, Sector-wide challenges, Vendors, Vision and Implementation decision. Lastly, the chapter presented the results of the questionnaire which measured absorptive capacity within TSO/DSOs and established findings around the aspects: (First) Source of Awareness/Interaction point, Decision to implement Digital Twins, Adoption Barriers and Budget Allocations.

6

CONCLUSION & DISCUSSION

This is the concluding chapter of the thesis and it begins by describing the findings over the course of the research in order to answer the defined research questions. After concluding the findings of the research, the limitations of the research and associated methods are presented. Next, the author reflects upon his thesis work from three perspectives: academic, societal/managerial and personal. Lastly, this chapter ends by highlighting the relevance of this thesis work in the broader context of the master programme: Management of Technnology.

6.1. RESEARCH QUESTIONS

This section is aimed at answering the central research question and the sub-research questions as defined in section-1.2.3. The answers to the research questions are in essence, the conclusions of this research and do not include or introduce any new information that was not known prior to reading this chapter.

***Central RQ**: How can digital twin adoption by grid operators in the Netherlands be explained by a technology adoption model?*

Digital Twin adoption by Dutch grid operators can be explained by several technology adoption models. In order to explain digital twin adoption in a comprehensive manner the following four steps were taken: i) Establishing the most fitting adoption model, ii) Determining the relevant adoption variables, iii) Examining the perception of digital twins in the industry and iv) Investigating the relationship between absorptive capacity and organizational characteristics. It was found that the most fitting adoption model when it comes to digital twin adoption in the Dutch energy sector was the Technology-Organization-Environment (TOE) Framework with the following adoption variables: Complexity, Compatibility, Perception, Technological Characteristics, Availability, Organizational culture, Organizational size, Budget size, Incentives, Management support, Absorptive capacity, (decision-maker's) Demographics, Attitude towards technology, Regulations, Competitive pressure and Network effects. In addition, the overall perception of digital twins was found to be positive across the Dutch Energy sector, however, there was no consistent relationship established between organizational characteristics and the levels of digital twin perception. Similarly, the research suggested that organizational characteristics and absorptive capacity were not correlated.

- ***Sub-RQ-1**: Which existing technology adoption framework(s) is the most fitting when it comes digital twin adoption?*

  There are several technology adoption models that can be applied to the case of digital twins. The criteria to select the most-fitting adoption model in this research was based on the characteristics of an emerging technology. Characteristics of emerging technologies (ET) among others include: ET Uncertainty, ET network effects, ET costs, Unobvious impact, limited availability, limited know-how/research, unpredictability in industry standards, business models and pricing. These features were mapped into five categories: Technological Characteristics, Adopter's demographics, Adopter's perception, Organizational factors and External factors. Technology Acceptance Model (TAM) Extensions, Diffusion of Innovations (DOI), Unified Theory of Acceptance and Use of Technology (UTAUT), Technology-Organization-Environment (TOE) Framework and Lacovou et. al model consisted of most of these categories in some form; however, since our scope was to analyze adoption at the firm level and not only at an individual (employee) level: DOI, TOE and Lacovou et. al model were fitting the context of this research. Although DOI and Lacovou et. al model analyze the adoption at a firm level, they give limited to no considerations to the nature of the technology itself. Since, digital twins are emerging technologies in their infancy, analyzing the technological perspective was deemed essential, hence the TOE framework was chosen as the most fitting adoption model. Furthermore, the TOE framework was found to be more comprehensive relative to other models allowing for a higher degree of freedom to include other relevant adoption factors/variables. Therefore, in the context of this research the TOE framework was selected as the central model of adoption. Moreover, to combat for the fact that the TOE framework takes limited account of the adopter's perception- aspects related to perceptions from the TAM extensions were also included in the framework.

- ***Sub-RQ-2**: Which variables are relevant in the adoption of digital twins by grid operators?*

  Based on the research conducted, there are five technology-based variables, eight organizational-based variables and three external variables that are relevant in the adoption of digital twins by grid operators in the Netherlands. The pertinent technology-based variables include: Complexity, Compatibility, Perception, Technological Characteristics and Availability. The organizational-based variables consist of: Organizational culture, Organizational size, Budget size, (Employee) Incentives, Management support, Absorptive capacity, (decision-maker's) demographics and attitude towards technology. Whereas, the external (environment) variables include: Regulations, Competitive pressure/behavior and Network effects.

6

Of the many variables, the focus of this research was on select variables: Absorptive capacity, Organizational size, Budget size, Complexity and Perception of digital twins with the principal inclusion criteria being feasibility of measurement. Organizational size, Budget size and Complexity were established as 'known variables' as they were measured/observed by the author by conducting desk research. The 'known variables' were operationalized by using the number of full-time employees (FTE) for organizational size; net profit for budget size and grid circuit length for complexity as proxies. Perception and absorptive capacity were qualified as 'unknown variables' that were studied by the means of conducting (semi-structured) interviews and targeted questionnaires with technology adoption decision-makers within Dutch TSO/DSOs.

- ***Sub-RQ-3****: What are the perceptions of Dutch grid operators when it comes to digital twins and how do they differ with TSO/DSO characteristics (such as: organizational size, net profit, circuit length)?*

The perception of Dutch TSO/DSOs when it comes to digital twins remains positive in some aspects, whilst mixed in others. TSO/DSOs have a good level of understanding/awareness of digital twins, which was witnessed by the various digital twin types (classifications) mentioned during the interviews. The fact that all TSO/DSOs perceive predictive maintenance and demand forecasting to be a potential use-case of interest for their organization is representative of the current challenges faced by the industry through the means of the energy transition and the increasing (variable) energy demand from consumers. Furthermore, their interest in digital twin use-cases arises from both internal drivers such as: operational efficiency, reduction in asset down-time, employee training, simulation, cost savings, and alignment with core values and external drivers like: regulatory pressures, customer expectations, and market transparency. In order to experiment with digital twins, most TSO/DSOs have already implemented pilot projects within their organizations, whereas some are still in the research phase and smaller-sized TSO/DSOs are unlikely to implement pilots in the near future due to limited resources. The (potential) impact of these digital twin pilots have been diverse across TSO/DSOs: increased worker productivity, automation of administrative tasks, increased worker hands-on time and flexibility in managing consumer demands. Having said that, a couple of large-sized TSO/DSOs have also been skeptical of the potential impact of digital twins so far citing that it was too early to generalize their impacts and they would not add any value unless standardized across the energy sector. In addition, TSO/DSOs do not view significant risks to data security or privacy with the adoption of digital twins at present on the grounds of stringent (stringent) data privacy/security laws that are in place in the Dutch energy sector. On the contrary, TSO/DSOs are concerned about becoming path-dependent, i.e., excessively trusting and over-relying on digital twins even in the case when they do not entirely represent the physical asset or its state accurately. When it comes to the challenges faced by TSO/DSOs around the digital twins, difficulties in limiting the scope of the digital twin use-case/application is recognized as a recurring issue (e.g.: applications like asset-steering require higher levels of accuracy relative to predictive maintenance). Small-sized TSO/DSOs face more obstacles in the adoption due to limited availability of resources (both capital and human/employees) at hand. Lastly, sector-wide, some TSO/DSOs are of the view that management teams possess limited understanding/knowledge of digital twins to take conclusive decisions around digital twin initiatives, whilst others view the reluctance of regulators (digital twins are operational expenditure and not capital expenditure) as an hindrance to the adoption of digital twins.

Overall, the perception of digital twins appeared to be positive across the Dutch TSO/DSOs. Having said that, there was no consistent relationship established between organizational characteristics (organizational size, net profit and circuit length) and the levels of digital twin perceptions except for the fact smaller sized TSO/DSOs seemed to be relatively less aware on aspects of digital twins such as: definitions/classifications, sector-wide challenges and vendors and less capable of deployment due to limited availability of resources at hand. This however, does not imply that organizational characteristics (organizational size, net profit and circuit length) and levels of digital twin perceptions in TSO/DSOs are entirely uncorrelated (or correlated); there ought to be further research conducted with more decision-makers at TSO/DSO in order to collect more data points and establish a significant relationship.

- ***Sub-RQ-4****: What is the relationship between TSO/DSO characteristics (such as: organizational size, net profit, circuit length) and organizational absorptive capacity?*

  In this research, Organizational Absorptive Capacity of TSO/DSOs was measured on four constructs: Acquisition, Assimilation, Transformation or Exploitation. On the aspects of acquisition and exploitation all TSO/DSOs were rated as having high levels of Absorptive Capacity irrespective of their organizational size, net profit or the (grid) circuit lengths they manage. On the other hand, when it comes to the dimension of Assimilation, large-sized TSO/DSO with high budget-size and low grid-length, large-sized TSO/DSO with high budget-size and high grid-length and small-sized TSO/DSO with high budget-size and high grid-length, portray low (assimilation) absorptive capacity. Similarly, apart from the large-sized TSO/DSO with high budget-size and high grid-length all other TSO/DSOs exhibit high (transformation) absorptive capacity.

  To conclude, all TSO/DSOs exhibited high levels of absorptive capacity when it comes to Acquisition and Exploitation irrespective of their organizational characteristics (organizational size, net profit or circuit length). On the aspects of Assimilation and Transformation, some TSO/DSOs were rated as having low Absorptive Capacity, however, this was not related to their organizational characteristics. Therefore, the research suggests that TSO/DSO characteristics (such as: organizational size, net profit, circuit length) and organizational absorptive capacity are not correlated. However, given the two factors: low questionnaire respondents (7) and (organizational) bias of respondents, the strength of this found relationship should be further investigated in future research.

6.2. LIMITATIONS

The research work conducted has a few limitations that must be considered before conducting future research. Firstly, the number of respondents of the targeted questionnaire were only seven, which may not provide us with conclusive evidence of the relationship between organizational absorptive capacity and TSO/DSO characteristics. Given the number of responses, the findings from the questionnaire can only be considered as an initial indication rather than a conclusive relationship. The limited sample size of respondents are not entirely representative of the entire population of technology adoption decision-makers within all the TSO/DSOs in the Netherlands. The prime reason for the low number of responses is due to the fact that questionnaires were sent to the participants after the interview was conducted as a follow-up email. Most interview participants did fill-in the questionnaire, however, it appears to be that limited or no participant actually forwarded the questionnaire to other technology adoption decision-makers within their organization, so as to collect more data-points. A strategy to overcome this limitation in future research could be to ask interviewees the contact details of other decision-makers within their organization and send the questionnaire to them directly rather than the current approach of having the interviewee do the work of forwarding the questionnaire.

Secondly, like with every qualitative interview method, the insights provided by the participant may not be entirely representative of the organization's (TSO/DSO) view on digital twins. The findings are entirely based on the views of technology adoption decision-makers that were interviewed. Therefore, it is possible that findings do not entirely represent the views of TSO/DSOs on digital twins. In order to overcome this limitation, additional interviews (with the same set of questions) should be conducted with other decision-makers within the same organization to get a clearer picture of the organizational view on digital twins rather than the individual's view alone.

6

Thirdly, the majority of the participants in the study were from well-established larger TSO/DSOs. There was limited representation of regional smaller TSO/DSOs: Apart from the participation of Westland Infra in the research, Rendo Groep declined to not take part in the research on the grounds of having limited to no awareness of digital twins. Other regional DSOs: Cogas (Coteq Netbeheer) and Enduris (part of Stedin Group), were not available despite several attempts to reach out to them via email and Linkedin. Out of the eight interviewees, there was only one interviewee from the regional DSOs, which may imply that the perspectives of smaller (regional) DSOs are underrepresented in the research. For further research, the focus should also be on collecting data-points from these regional DSOs and not only the well-established national TSO/DSOs. A fourth limitation of this research is that it is restricted to only energy market participants in the Netherlands; which makes it difficult to draw conclusions on the adoption or the perceptions of digital twins in the broader European energy sector. In order to tackle this shortcoming in future research, TSO/DSOs from other parts of European must be considered in the research. Lastly, when measuring absorptive capacity of an organization, the participants were asked to mark statements about their organization via the questionnaire; we should keep in mind that this approach may introduce bias as employees may tend to be less critical of their organization in external surveys especially when competing firms are involved in the research.

6.3. REFLECTION

In this section, the author reflects back on to the research work conducted during the thesis period from an academic, societal/managerial and a personal point of view.

6.3.1. ACADEMIC REFLECTION

The research work has been intellectually stimulating at several fronts, from building the conceptual digital twin adoption model to validating parts of the model. Firstly, an interesting point to reflect upon is the divergence between digital twin classification in academia and the industry. As mentioned in section-2.1, existing academic literature delineates three types of digital twins based on the lifecycle stage of the physical asset: Digital Twin Prototype (DTP), Digital Twin Instance (DTI) and Digital Twin Aggregate (DTA). However, during the interviews it was observed that there was no common ground to classify digital twins in the industry. An interviewee classified digital twins based on their (increasing) level of complexity into 4 types: Visual Digital Twins, Data-based Digital Twins, Interactive Digital Twins and Autonomous Digital Twins. Another classified them based on interactivity with the physical asset into: Static and Dynamic Digital Twins. Whereas another interviewee mentioned a classification based on work environment where digital twins are (proposed to be) used in their organization: Internal Digital Twins (for internal work streams) and Network Digital Twins (for the grid). These different methods of classification do not necessarily result in mutually exclusive digital twins or do not imply that there is no overlap among these classification methods, but rather suggest that there are limited classification standards which are widely accepted/used both in academia and the industry. The lack of standardization in digital twin classification could possibly stem from the fact that digital twins are still in their early stages of adoption and there are uncertainties around the definition of what a digital twin is.

Another fundamental point of reflection, in my view, are the constructs of perception. As described in section-3.1, perception associated with technology adoption is defined into three constructs in most scientific literature: Perceived Ease-of-Use, Perceived Usefulness and Perceived risk. Apart from assessing these three constructs alone during the interviews, we included other factors such as awareness levels, potential use-cases, potential impacts, vendors and sector-wide challenges among others. Using ten constructs to assess digital twin perception in TSO/DSOs enabled us to gain a holistic view rather than only looking into the perceived risk, benefits and ease-of-use of the technology. I am of the view that the perception of a technology, (especially emerging technologies like digital twins), may be influenced not only by the perceived risk, benefits and ease-of-use but also by the level of awareness/knowledge that individuals/organizations possess. In simpler words, when an entity is relatively less informed of an emerging technology, his/her perceptions of the technology are likely not entirely representative. Hence, in future research an interesting hypothesis to identify/validate could be the relationship between an organization's digital twin awareness levels and its perceptions.

6.3.2. SOCIETAL/MANAGERIAL REFLECTION

There are three elements that come to mind when reflecting upon the thesis work from a societal/managerial perspective. Firstly, whilst researching digital twin adoption variables, I came to a realization that technology adoption decision-making in itself is complex. Apart from the technology in question, management teams and decision-makers must think critically of several 'moving parts' or attributes before making any decision. This research work provides management teams with the foundation of variables that they ought to consider when making their investment decisions around digital twins. Although, the list of variables may not be entirely exclusive or exhaustive at this stage, managers can still use the developed model to brainstorm each aspect and add/remove variables as per their specific context, observations and findings.

Secondly, for technology managers at TSO/DSOs, the research confirms that the potential digital twins use-cases of interest that they are currently or intend to pursue are proven and backed by academia. Put simply, the potential use-cases of digital twins in the energy sector found during the desk research phase match the use-cases discovered during the interviews. Therefore, in all the ambiguity around digital twins, the relevance of this research work for technology managers is hidden in the fact that it provides the most up-to-date market sentiment around digital twins and the impression/progress of competing TSO/DSOs in the Dutch energy sector.

Lastly, from a societal point of view, in the broader context digital twin applications enable the acceleration of the energy transition for grid operators. This implies that grid operators with digital twins are empowered to achieve their Sustainability Development Goals (SDG) by reducing emissions and other pollutants from the electricity grid and moving to more renewable sources of energy. Hence, the positive perception of digital twins, as discovered in the the research, illustrates immense value for both the energy sector and the society when it comes to sustainability-related initiatives.

6.3.3. PERSONAL REFLECTION

Coming into the final phase of the study with the master thesis, the world was still struggling to combat the COVID-19 pandemic. With extended family affected by the virus, it was particularly difficult to stay on-track with additional university courses, managing (thesis) expectations and working externally at the same time. Apart from the academic rigor, the one thing that I learnt over this thesis period was the importance of resilience. Before coming into the master programme, I would not have expected myself to be able to justice with the performance at university courses during these COVID-19 times and balance extracurricular activities on the side. Once the master thesis kicked-off, the eminent challenge that I faced was to scope-down the research problem into a more feasible problem which could be addressed over the course of the thesis period. More specifically, I had a tough time limiting down the variables of interest that ought to be studied further through the research. Having said that, I was able to tackle this challenge by carefully reflecting upon the feedback from the graduation committee; this is when I learnt that the value of critical feedback not only comes if one just executes it, but when one takes the time to reflect upon the feedback itself.

Thirdly, I consider myself as more of a quantitative person by nature and found qualitative research distinctly more demanding. As a result, I was initially biased towards developing hypotheses that could be quantitatively accepted or rejected rather than taking the challenge of conducting qualitative research. Eventually, I learnt that the qualitative approach fits more with the research problem of exploring the current perception of digital twins. Hence, the decision to convert the hypotheses into sub-research questions for the remainder of the thesis period was made. Reflecting upon this decision, I have understood the value of qualitative research and being able to look behind the numbers. As a final note, I can now look back and ascertain that this (thesis) experience has helped me both as a student and as a professional. This period thought me several matters that I will utilize as takeaways in my professional career. Among other things, I learnt how to be in-charge of your own project, deliver upon promised outcomes and manage expectations when several stakeholders are involved. Another essential (intangible) takeaway for me was to realize the importance of critical thinking in both the academic and non-academic work environment. Lastly, I reflect upon the fact that these takeaways would have not been made possible without the perpetual support of prof. Ben Wagner, prof. Yilin Huang and prof. Frances Brazier. Writing my thesis under this graduation committee has been a thought-provoking experience that I will always value.

6.3.4. MANAGEMENT OF TECHNOLOGY PERSPECTIVE

The central idea of the Management of Technology (MOT) master programme is to empower students to explore and realize the value of managing technology as a corporate resource in professional organizations. Along the same lines, the thesis incorporates aspects of the coursework that enables both technology managers and researchers to address questions that are relevant when making the decision to adopt digital twins. The thesis lays the groundwork for technology adoption-decision makers by investigating the relevant variables when it comes to digital twins and provides insights into the elements that decision-makers ought to keep in mind when thinking about technology adoption. From an academic (coursework) point of view, this thesis was inspired from three core MoT courses namely, MOT2421 Emerging and Breakthrough Technologies, MOT1524 Leadership and Technology Management and MOT2312 Research methods. In MOT2421 coursework, technology adoption models were introduced, although mainly the Technology Acceptance Model (TAM), but it served as a starting point to investigate technology adoption models further for the case of digital twins in the energy sector. MOT1524 encouraged the author to look at digital twin adoption also from the point of view of the decision-maker. In most cases, technology adoption decision-makers in an organization are experienced management teams that are not only concerned with technology selection but need to also be well-versed with its (potential) commercial impact for the organization. Hence, the author provided a comprehensive perspective of the digital twin adoption variables and did not solely focus on the digital twin technology in itself. Lastly, MOT2312 introduced the intricacies in research methods such as: interviews, questionnaires, data management and triangulation among others, which were utilized in the development of this thesis. Therefore, both the building blocks and the outcomes of this thesis are aligned with the expectations of the MoT curriculum.

APPENDIX-A

INTERVIEW TRANSCRIPTS

This section includes transcripts of interviews that took place with eight technology adoption decision-makers across TSO/DSOs in the Netherlands. Keeping in mind the privacy of the participants, the transcripts have been anonymized.

INTERVIEW-1,2

Director, Member Management Team and Chief X Officer at a Large-sized TSO/DSO

1. **A digital twin is a virtual replica of any physical asset. How does your organization see what a digital twin is?**
   I agree with your definition for the most part. However, I make a separation between the system and the network as we are transitioning towards the new energy system. We first, look at the transition of the entire system and then, we go towards the network. In essence, it's basically a simulation of the outside world, so we can make judgement calls or decisions sitting from behind our desks.

2. **In your opinion, what would be the potential digital twin use-cases for your organization?**
   We have a few use-cases running on the demand-side both quality and capacity. In every energy use-case, you need to have system balance, system safety and system availability; therefore, you need to have a digital twin up-and-running to avoid regret costs/actions as I call it. We have a few use-cases on predictive maintenance and replacement of assets to base our investment decisions. In the latter, we initially used two data inputs and that has now been expanded to ten. So, a digital twin helps us to predict when we need to replace our assets and invest again, but also to see where we are having issues in the grid before the customer gives us a call. Therefore, we have various use-cases running on digital twins in our organization.

3. **Why is your organization interested/motivated to consider investing in Digital Twins?**
   Operational efficiency and market transparency are a few reasons why we are interested in digital twins. The more insights you have on the forecasts of your assets, the more perspectives you must take actions on; and the more actions you have to align with your strategy. In short, if you have a digital twin up and running, the more capable you are to execute your strategy for the longer time. What has changed over time is that: initially, digitalization projects like digital twins used to have internal drivers, so that we could better do our jobs or be more effective with our investment decisions or maintenance plans. But what we see happening

now is external drivers like legislation are becoming more demanding. In order to fulfill these obligations from our regulators, customers or stakeholders, we basically need a digital twin to be up and running. Some regulatory drivers include sustainability and digitalization of the energy sector.

4. **How far are you in the development of a twin / implemented digital twins in operations already? Why?**
   I would say we are in the pilot phase. Of course, we have a system in place that tells us what happening now on our grids and/or assets and if you need to act – we call it 'BWC' (in Dutch). This system is, however, more on the outlook, the network operation system I call it. A digital twin is more about modelling and predicting what's going to happen in the future (5 or 10 years)- and, this is something not in place yet as it should be. With pilot projects, we are trying to adopt digital twins. At our organization, the first steps towards a digital twin pilot project took place about 3 years ago when we saw a lot of congestion on the network, and we wanted to add more capacity.

5. **How could you describe the (potential) impact of digital twins on your existing company processes/applications?**
   The difficulty is to generalize the impact of digital twins. In some use-cases, digital twin reduces the total cost of ownership by 10-20%, sometimes even more. But, sometimes, it does not reduce the cost, but then we are sure that we are performing the right level of maintenance or making the right investment decisions. It's quite tricky to give generic numbers about the impact of digital twins, for example, digital twin reduces 10% of costs on average. However, digital twins do have significant benefits. Based on a digital twin, you are capable of making the right investment decisions. You have separate levels: High Voltage, Medium Voltage and Low Voltage: - by decentralizing the energy system there are more upcoming dynamics in the low voltage parts of system. From my perspective, a digital twin (pilots) so far has improved our risk planning and asset maintenance. At the moment, we cannot generalize the impact to every use-case out there.

6. **What are your thoughts on the risks and benefits of digital twins? Given equal risks and benefits, would you or not take the decision to use them?**
   I think the risk is that if we don't develop a digital twin in the end, it will affect our license to operate as it's not only internally driven but also externally driven. Business wise, there are several benefits associated with it. In some circumstances, it may improve the data quality, in others, it may significantly reduce our cost to serve. In other cases, it may help us make more effective investment decisions or more accurate long-term maintenance plans. Risks of data security and privacy comes in the next phase when market interaction via adoption increases (let's say after 2025), for now, it is not a major risk of digital twins. In the future, we need to be prepared that we have two-way communication with our smart devices to balance and secure the system by taking measurements remotely.

7. **In your opinion, what are the challenges to digital twin adoption in the Energy sector?**

The challenges to the energy sector are a part of the approach, I mentioned earlier: System Balance, System Security and System Availability. The goal for the entire energy market, we say is decentralizing the system, introducing new energy forms (e.g., heat or hydrogen), but at the same time, we must keep the system in balance, safe and secure. Smaller DSOs who have limited resources should work closely together with other market participants and the TSO. Digital twins are not only regionally important, but also nationally important for the grid to keep the whole system in balance.

8. **Are you aware of any suppliers who can implement digital twins for your organization? Have you contacted them?**
   In our initial pilots, we made an IT architecture in-house to achieve OT and IT integration. And, then we finalized our architecture model, and now we are filling in that model. We also separated digital twins in to two for our organization: Operational digital twin and Strategic digital twin. We are now planning to roll-out and implement the whole architecture that we have chosen and that's a 2–3-year planning. You could argue that we have some kind of digital twin with our Geographical Information Systems (GIS), but, the thing is that we are now developing it so that we can use it in a more dynamic way in our business decisions and daily work. It also depends on how you explain what a digital twin is. For running our business, we have our operational center, where we see what's happening on the network now. The most important feature of a digital twin is that, based on the right data inputs (from the smart devices installed at the grid), we can get more insights, which you can use in modelling and forecasting conditions.

9. **If the decision to implement digital twins in your organization today was solely in your hand, would you, do it?**
   Out of time

INTERVIEW-3
Innovation manager at Energy supplier

1. **A digital twin is a virtual replica of any physical asset. How does your organization see what a digital twin is?**
   I think it's very close to how you define it. What we want to have is a digital representation of the assets we have in place to get an understanding of a number of things. The business that I am in is district heating. In district heating, as opposed to for example electricity, our grids have delay factors and are very influenced by the outside conditions. For example, if the weather is cold, it's going to influence not only the demand for our product, but also the actual transportation of the product. For us, this creates another layer of complexity, so it's not just what you understand on paper, but there are also factors that you can't process on paper. As such getting an understanding of how our grid works as a whole is very important – this is where digital twins really create value for us. So, digital twins are basically a virtual representation of what is our asset base and the system, so that we can simulate it under various conditions and understand how it functions.

2. **In your opinion, what would be the potential digital twin use-cases for your organization?**
   The first digital twin that we created was a simulation or a digital representation of our heating grids in one of our largest city grids. In the past the cost of transporting our product (heat) was very low and there was not really a growing demand for it. However, now as we are moving away from gas a source of heating, the central district heating product that we offer are more in demand and the price of it is increasing. As such we need to maximize the use of it. Before, we used to produce heat, let's say centrally, and we pump it towards our customers, and we guaranteed a certain temperature (e.g., at 70 degrees). However, between the production site and the customers, we don't know what happens here. We only know the temperature at which the heat is sent from the production site, and we never measured it intermittently. So, what is the temperature in between during transportation on the grid and how can we reduce or increase the temperature to get what we promised to our customers. Because of the delay factors and the deterioration of the grid, ground temperature or bypasses in the system, we did not know how actually the grid performed. So, we used to pump as much hot water as possible to ensure that we met client demands. But now, by simulating these grids, we can start lowering the temperature of the heat and reducing the heat losses we have and maximizing the use of the heat that we produce.

3. **Why is your organization interested/motivated to consider investing in Digital Twins?**
   It's both financial and sustainability related drivers. One of our missions is to speed up the energy transition and make the energy transition for everyone. If we want to do this, we need to maximize the use of the heat that we have. Sustainable heat is a scarce source – so, as such we want to make sure that we can deliver it to as many customers as possible. And that means really focusing on maximizing its use and

obviously this of course has financial benefits to it. Although, it's not a priority- 'if I had my money to put somewhere, it would not be the first place to put it'. It's not the most incredible business case. Having said that, it does deliver value especially on the sustainability front, which is very important for us, therefore, digital twins are something that we pursue. On top of that, they also can save some operational costs as they make the grid more efficient.

4. **How far are you in the development of a twin / implemented digital twins in operations already? Why?**
We have digital twins that are running in operations and not only as pilots. We have a digital twin that is running full-time because it's part of our operations. Now, the question is: how rich a digital twin is. We have continual measurements at our production site; we have continual measurements at our distribution station; and we have continual measurements at our clients where we have smarts meters in place which feeds into the digital twin, and we get an understanding of how the grid works at every moment. But you could add more sensors or add more data – so, it's not so much the question of if you have a digital twin, but, how rich or how much data does your digital twin process. However, we have not covered digital twins in all our use-cases yet, there is still so much more we can do with it. We use these models also on different dimensions: understanding grid capacity in the long-run and grid optimization on a daily basis. Let's say, in a particular section of the grid I want to add more customers, do I have sufficient capacity to add them? – that is also something we can do with digital twins. However, you don't require real-time data to do so, but it's a different dimension of the digital twin use case.

5. **How could you describe the (potential) impact of digital twins on your existing company processes/applications?**
About three years ago, we decided to implement a digital twin in our operations. Before the launching into operations, we have had to do different pilot projects to get there. I would say, the digital twin is fully operational since about a year and we are still considering which of the models to pursue further as we have two models in place from two providers. Initially, we did not call it a digital twin to be completely honest, that is more of a modern term. For us, it was a simulation and an optimization tool. In fact, most people at our company don't call it a digital twin. They call it a forward temperature optimization tool or heat simulation tool or something like that depending on the application and the use-case at hand.

6. **What are your thoughts on the risks and benefits of digital twins? Given equal risks and benefits, would you or not take the decision to use them?**
We are not entirely sure of all the potential benefits to be honest. Our specific use-case is clear, so we know the benefits of digital twins in this case. But there is so much spin-off of a digital twin that is possible and not quantifiable which makes it hard to make an all-encompassing case. In our situation, the use-case was convincing from the beginning, so as such, we did not have to broaden (look into) all use-cases to make sure that we can capture the benefits. In terms of costs and risks, digital twins or simulation/optimization tools like we call them, require an in-depth understanding of the grid itself – and that's where the scarcity in resources

becomes an issue. There are only a handful of people who really understand how it works and can explain it. So, knowledge is a key aspect – Not necessary knowledge with the service provider/supplier, but knowledge within the organization is key. And, if we don't have the knowledge internally, there is limited chance of success. Furthermore, anything to do with digital transformation these days has to do with data security and privacy issues. This is something you just need to tackle in the projects – ensure that you built in the right security measures, make sure that you get permissions from clients to use specific types of data if necessary. Data security and privacy is a factor, but it is a logical predictable factor, and you know how to mitigate this risk as it comes with every digital transformation project.

7. **In your opinion, what are the challenges to digital twin adoption in the Energy sector?**
   Investment is a huge one. The reason that we have been able to do digital twin projects in parallel with our current operations is that we have had to make significant investments in smart meters, and we'd have to make these investments anyways. But, because we have smart meters in place already, we have the data in place for digital twins. The technology that we use now, 4g/5g enables this move to digital twins as opposed to other electricity and gas DSOs, who may have made this investment earlier than and us (let's say 10 years ago) and yet can't do this. So, they might be first in their investments in digital twins but can't really create/deploy one with the data they have now. Whereas we were able to do it (deploy digital twins) cheaper, faster and make a big leap despite being some years behind. Furthermore, we are convinced that the future of energy is not going to be across one medium. Energy in the future is going to move from power to gas; gas to heat; heat to storage; and so on. Energy is the future is going to be across mediums and go forward and backward. In the future, a client is going to produce energy when it has excess and deliver it back to the grid, and at other times it consumes from the grid. So, we are going to have to make a million decisions at a time and we can't do this as individuals anymore – it becomes complex. You have to start simulating, for instance via machines learning applications to make these decisions for you. Companies that have sufficient resources to make such investments are going to be the only ones that survive. I think, the future is going to be with a very few energy providers who basically control the entire system because they are able to make these huge investments relative to smaller energy providers and/or DSOs.

8. **Are you aware of any suppliers who can implement digital twins for your organization? Have you contacted them?**
   The first supplier approached us, and after a while also the second supplier – so, both parties approached us. These two digital twins are very specific and were developed specifically for the district heating market and are not applicable to other markets. As such, if the vendors are trying to sell their digital twins, there are only a limited number of companies that provide district heating which you can approach. In the Netherlands, there are three large firms and then you get to us at the top of the list. I would say: they approached us, showed us the value of their digital twins and we took it from there – it was not something that we initiated.

The second supplier knew that we were doing a project with the other party and said they could develop something like this as well. We basically did a pilot project with both these suppliers, and we now have digital twin running in our operations. We are now looking into doing a pilot for one of our other grids as well.

9. **What is the vision of your organization and how does it align with the adoption of digital twins?**
Our organization has always been about decentralizing power, but also ensuring that everybody can participate in the energy transition. Digital twins are going to be key for us to achieve this vision. If you don't consider digital twins, you can't squeeze out all the value of the scarce sustainable power. The challenge is always going to be managing sustainable energy and optimization methods such as using digital twins are going to be key in that. In the future, the term digital twins is going to be more specific, it is too broad a term now and encompasses a variety of different applications. Two, in the future, we are going to be able to combine data at a way faster pace than before, the value of sensors is going to down, value of data transportation and telecom costs are going to go down. So, you are going to be able to deploy digital twins more easily in the future. As such digital twins are going to be ubiquitous across the energy landscape. However, capturing the value from digital twins may remain difficult for some.

10. **If the decision to implement digital twins in your organization today was solely in your hand, would you, do it?**
Of course, its obviously the way forward. Data-driven optimization is a no-brainer. There's no way we are going to be able to realize the energy transition without doing it.

INTERVIEW-4

Architect at Large-sized TSO/DSO

1. **A digital twin is a virtual replica of any physical asset. How does your organization see what a digital twin is?**
   The granularity of a digital twin is an important aspect when we define what a digital twin is. We tried to project a physical asset on a virtual computer node. We saw that if you try to create a virtual node for every equipment on our network, then there are way too many nodes. As a first step, we tried to replicate the state in the context of a sub-station as a digital twin rather than every smaller component.

2. **In your opinion, what would be the potential digital twin use-cases for your organization?**
   The use-case depends on what we call a digital twin. Digital twin is a concept and there's not a clear definition. I came from a data management advisory role and at that time we were trying to put digital twins on the map for our company. One of the challenges for utility companies is having a clear perspective of everything you have – your asset management and your state. So, things like how everything is connected, what kind of information do we have and what is the state of our assets. Most of the digital twin use-cases needed enabler. For instance, we would do predictive analytics on our assets, but it is not the same as having a digital twin. So, our focus was: if we bring together the state of the grid and the connectivity of our assets, then we can do digital twin use-cases. You can question if the connectivity model, assets and the states together is a digital twin or not – however, it is relevant for the company as we need all those three things. We tried to put all these three together via a digital twin to get all the information of a given asset in a decentralized way. We called it 'Agent-based Digital Twins'. So, all this information/data is not in one big database or in an asset management environment. Our idea was to make all these agent twins running their node that represented a digital twin and extract (put) all the related data/information from there. A digital twin was mainly an enabler because we needed asset information for all the solutions like you mention predictive asset management or calculating risks of outages. Centralizing data into one big database is not scalable, so, we thought of agent-based digital twins with decentralized aspects of our grid that represent the data and are responsible for collecting and maintaining the data on its own. So, it was a combination of digital twins and edge computing. There is also real-time flow of information between the agents.

3. **Why is your organization interested/motivated to consider investing in Digital Twins?**
   Demand from customers or regulations is not the main factor that caused our interest. The ongoing challenge of being in control of the current state of your grid – if you are working in the field, you want to know what you are going up against (e.g.: what is the environment I am walking in, are there any complexities, etc.). Solving this field-worker perspective made digital twins interesting for us. Second, the other perspective or factor of interest was from an engineering point of view

in extensions of sub-stations. So, sub-stations are large plants in the environment and if you want to place another transformer, for example, an engineer's needs to have the most actual image of the environment. Third, from a simulation perspective, if you had the sub-stations connected, we could calculate how current flows or what happens if one transformer fails and what happens to the environment. In short, there are namely three factors of interest: field-worker perspective (what am I walking into), engineer's perspective and the simulation perspective.

4. **How far are you in the development of a twin / implemented digital twins in operations already? Why?**
To pinpoint the specific digital twin solution, I can't because we stopped doing the initiative that was digital twin, but we still do all the use-cases around digital twins like: simulation, and predictive analytics. We have a connectivity model, and you can argue if we a digital twin or not. Some say we have a digital twin, but we don't have it developed as the entire digital twin concept within our organization. We tried to deploy the digital twin concept, but it did not land in the management team. So, we have now more like an under-layer that is developing on its own, so, there's not something specific that we can pinpoint and say that's our digital twin approach. We thought of our first digital twin pilot back in 2017 from the High Voltage sub-net. Digital twins are mostly relevant where the risks are higher – high voltage network had the most outage impact, so we tried to deploy digital twins on this part of the network. However, the deployment of the digital twin did not happen as the management of the organization i.e., the service provider of this high voltage net did not have this need of urgency. When you are doing service provisioning on an electrical network, then you are focus is mostly one of the two use-cases: field management (I must send my engineer to the field, and they have to know servicing). But the asset-owner has a different perspective: they want to know what my asset portfolio is and what it's state. So, you have different perspective in the organization: asset-owner and service provider, that did not match up, which translated into different needs and that's why the digital twin deployment did not happen. Service provider is the company that does the extensions on the network, maintenance and outage management processes. In our case, X (anonymized) is the asset owner and is responsible for all the risks in the net and investing in the net, but when you extend or maintain the net, you give this work on a contract to the service provider. So, service provider has a different need that the asset owner, but we are one company. So, from the operations part and the asset management part, we did not have the same strategies and the same needs.
From an asset owner perspective, the whole net is connected: so everything in X's (anonymized) grid is one and should be connected to a digital twin. But, from a service provider (contractor) perspective, there is only a certain part that you are providing service to. For example, if the service provider works on the high voltage sub-net, they are not allowed to see any other parts of our grid. So, asset owners wanted a digital twin for the entire grid, so as to do connectivity calculations for instance, and service providers wanted digital twins for fragmented parts of the net – there was no common ground to develop a digital twin, mainly from a use-case perspective. We tried to deploy a digital twin via this pilot for two and a half

years and in 2019 we tried our last efforts to get it at the management team of the service provider. Then, there were other challenges that came up like productivity challenges (we call it 'maakbaarheid'): We had too few people to realize the work that was coming from the asset owners – which is a big of a topic even today due to the supply-chain challenges we see all over the world. The digital twin was more of an innovation initiative, and it did not get the attention and was sidelined. It is still running within our organization at a very small scale within IT, but not from a business perspective.

5. **How could you describe the (potential) impact of digital twins on your existing company processes/applications?**
From a field service perspective, we saw that if engineers had to go in the fields and work with old systems – they had to do a lot of manual work before they service the system like going through the large technical drawings of the systems on the location. Hence, when going to the sub-station and something is wrong, engineers don't have the actual information and must collect info. from the SCADA system, work order history, etc. So, there was a lot of impact of the digital twin to get more hands-on tool time for the engineers as they had to do so many administrative tasks to get to their job/task before. In short, for the service provider, we really saw productivity benefits when using digital twins.

6

6. **What are your thoughts on the risks and benefits of digital twins? Given equal risks and benefits, would you or not take the decision to use them?**
We looked at it from a decentralized architecture and storage perspective – how are you going to maintain as its not completely autonomous and you have to do some sort of data management on it. For our organization, data management is a difficult topic because a digital twin is essentially information that you have to manage whether it's the state, 3D or time perspective. By decentralizing, it got increasingly complex to manage the data. We were only looking at it from a technology perspective, but from my role I saw a real challenge on how would be do the data management perspective: ownership of the data, where it the data, how would it be identified, etc – a lot of those questions have never been answered because we were only focused at technology perspective at first. Another challenge/risk was that the knowledge was missing from our organization. People did not understand the concept of digital twins and what it meant for them. People are only currently capable of thinking in what's this solution and how does it help in my current challenge. So, digital twins were not clear as a concept. Lack of knowledge is a risk that was definitely there and will continue because this is a long-term investment. Not everyone is on the same page when it comes to digital twins – there are only a couple of people understanding it and seeing it for the organization.

7. **In your opinion, what are the challenges to digital twin adoption in the Energy sector?**
We mentioned it already, the management of organizations do not understand what a digital twin really is. So, they have a need from a use-case perspective or solution, and I think digital twin on its own is not a solution - maybe it is marketed

like that, but it is not a solution. The challenge we faced was there was not management adoption or sponsorship in the end – nobody gave it any attention. So, it was a technology push, and we know technology push only goes so far. And I think that's the same challenge for all the utility companies not only electrical but also logistics and infrastructure partners. The management understanding of a digital twin is not the same – there is a disconnect between the perspective of the technology on how it should work for the organization.

8. **Are you aware of any suppliers who can implement digital twins for your organization? Have you contacted them?**
   We have done sessions with IBM for example, and a couple of sessions with Bentley systems. We did not only do it ourselves, but we saw what the offerings of vendors were from our own vision. As our organization, we are doing a lot of innovations. The offerings from the vendors and our ambition/challenges did not match. We had good conversations about what it is and how it would help us, but in the end, we did not want a single vendor's solution that was the solution for digital twins. One of the aspects was IoT, open data to connect nodes with each other from an open-source perspective – a conversation with IBM or with other vendors did not go that way. So, we did some sessions with vendors, but in the end, we did our own innovation track and started with what we learned and that's where we are today – so, it's a hybrid situation. In the end, we did not buy anything from the vendors to buy us into the digital twin.

9. **What is the vision of your organization and how does it align with the adoption of digital twins?**
   For our organization, I see there is a shift away from digital twins and that's why we stopped, and we are looking way more at our resources and supply-chain challenges – so, how is everything connected in the ecosystem from a process perspective. I think digital twins is going to the background and our focus currently is to make our production plans, meet our capacity targets and extend the network. And this focus does not really relate to doing something with a digital twin. A digital twin once again is an enabler for doing things better – but, from an information and sharing perspective, our challenges are really focused at doing more production, extending the network's capacity. I think all our infra partners, have the same challenges – really focused on the business challenges and not on how we can use technology, and I don't see how digital twins would help in that. So, for me, digital twins will remain on the side-track for a couple of years and that's also because of the supply-chain issues the pandemic created. So, the challenge has shifted way more to an urgency in business than in the last decade, where we could focus on emerging technologies like digital twins, work environment of the future. Most of these innovations have been turned down a lot due to the focus on existing business challenges. I do not see large-scale digital twin adoption in the next 3-5 years at least not at our organization.

10. **If the decision to implement digital twins in your organization today was solely in your hand, would you, do it?**

No, I would not take this decision with the knowledge I have today – it's not something that I can shine on. We tried to bring this to the management team already and I was convinced that this is something we had to do. But, it did not work – maybe it's because I did not do the right thing, but I think our organization was not ready for it anyway.

INTERVIEW-5

Innovation researcher at Large-sized TSO/DSO

1. **A digital twin is a virtual replica of any physical asset. How does your organization see what a digital twin is?**
   We normally define a digital twin, as a digital representative of what we have in the field – so, exactly how you define it: it can be whole grid or a smaller part of it. You don't often see a single 3D model as a digital twin, normally we see digital twin as a 3D model with some extra information to it. The 3D model could be interactive and get extra information from the physical asset real-time, but this application is still in the concept phase, and we do not have them deployed on the grid yet. But, you can also have a static 3D model, so you can walk around the grid and make the image smaller or bigger – but, if you can have some interaction with it, then it is more like a digital twin.

2. **In your opinion, what would be the potential digital twin use-cases for your organization?**
   I do see demand forecasting and asset predictive maintenance as potential use-cases, but they need to be researched further. For now, we did not or at least I did not research them in detail yet and I haven't heard about research studies in our field. With the knowledge I have now, I think these could be potential use-cases, but I must research further to be certain of what the possibilities are. So, indeed these use-cases are possible, but I am not going to 100% that this is going to happen.

3. **Why is your organization interested/motivated to consider investing in Digital Twins?**
   Well, I am interested in a digital because of my role and that I'm an innovation enthusiast – so, I can mostly speak for myself. We are doing some research on digital twins as they can be used for simulation, and maybe also use them for training. Those are two topics that I find interesting to research further upon what the possibilities of digital twins are. Operational benefits of digital twins could be interesting – if because of a digital twin you can link info. to an asset and easily acquire that info. in the field. Like I said, for now, simulation and training are interesting topics to think about when we talk about digital twins. More specifically, simulation of how the grid works or training on how to operate some assets or how do you work on a process with an asset – those kinds of things.

4. **How far are you in the development of a twin / implemented digital twins in operations already? Why?**
   We have had some projects related to research, but for implementing digital twins, we have not had pilots in our organization yet from what I know. Like I told you, we are still researching digital twins and whether we can link data to some asset and brainstorming on how we can use digital twins. On a scale of 1 to 10, I would say we are at 3 in the development of a digital twin. We are still in the initial research phases. I heard about digital twins about one and a half years ago from a colleague

of mine because that's when I started with my current role. In my previous role, I did not have much to do with digitalization.

5. **How could you describe the (potential) impact of digital twins on your existing company processes/applications?**
Assuming we have an idealistic world where we have everything a digital twin has to offer and the real-time asset data next to it, I think it would really help the workers when they start projects. Workers can easily prepare for projects – for example, if there's a blackout (big or small), they can with the digital twin, already find where the problem is and know how to fix it and know what to bring with them to the site. As I said, it would be easy to simulate things – we are curious for example, what is going to happen to this part of the grid if we are making a connection over here. It could also help people in the field, if you link digital twins to Augmented Reality. If you have all your information of your asset on you all the time and you have a digital representative on any device, it would be easy to go from the digital to the physical world and vice versa. Things like finding assets, knowing the state of assets and adjusting to systems becomes much easier. If you have a digital replica, it will probably reduce administrative tasks for employees which is also nice. Currently, we do have systems like ADMS and GIS, but if we are able to link all the data of an asset in one place like in a digital twin, that could be a major difference. The possibility of working from your digital twin on the physical asset also makes it easier.

6. **What are your thoughts on the risks and benefits of digital twins? Given equal risks and benefits, would you or not take the decision to use them?**
A major risk that I would say is what if a digital twin got hacked and you have all the data of an asset in it. The last thing you want is your energy grid being hacked and shut down. So, data security is one of the issues when you have all the data centralized and the risk increases when we are hacked. If a digital twin is built wrong, then data privacy could also be a risk. But I think there is really good regulation to safeguard privacy for example, regulation on what we can and cannot read from a smart meter. If a digital twin is built not keeping in mind the regulations, then data privacy could be a risk. But, when you are start building, you should always have the privacy of your consumers at number one. Therefore, I don't really think privacy is a major risk as our organization puts privacy of our consumers as one of our high priorities. It doesn't even come to my mind that we would build something that does not consider the privacy of our consumers so to say. So, you should have measures in place to tackle the cybersecurity risks that we talked about earlier. For example, if the data is leaked, there shouldn't be any names or personal consumer data available – these are things you should think of in advance. Hence, privacy issues should be tackled in advance in any organization, and they should not come as a surprise afterwards. Another risk that I see is data quality – what happens if you solely depend on a digital twin. For example, an engineer goes to the field completely relying on his digital twin and if the information provided by the twin is wrong – what happens then? So, if you build a digital twin with very poor data quality, then you get the classic: 'garbage in

is garbage out'. Then, even if we talk about all the fancy use-cases, the digital twin won't just work.

7. **In your opinion, what are the challenges to digital twin adoption in the Energy sector?**
   Let's again assume that we are talking about the entire digital twin package which is a one-on-one replica of the physical asset. Then you definitely have an enormous task at hand to build this. For example, to put every screw of the asset in the digital twin is a complex task because I don't know how many screws we have on our entire electricity grid, it's definitely not five so to say. Investment cost may be a challenge for later. For now, a bigger challenge is the problem of scoping – say for example, you want a digital twin, then on which scale or scope it actually becomes relevant, or you get benefits from having a digital twin. On which detail, should we have a digital twin – I think that is a research question first to figure out before you dive into investment costs. If you have the answer to that research question, then you also know whether the benefits of the digital twin outweigh the expenses of the investment. At this stage, I cannot point to how much investment cost will be. But, I can imagine depending on the scope investment costs may be an important barrier for some DSOs. Therefore, the first challenge is scoping. We already named some use-cases, but we have to scope them and figuring out things like: what use-case you want to use and how does that work? Of course, with any digital technology there's always culture – if you deploy a digital twin: how are people going to react to this? Will they think its nice? You can build the greatest car there is, for example, if people don't like the way the driver's seat looks, then they still won't drive it so to say. So, how are you going to make it user-friendly for everyone and that's also about scoping. Therefore, it's important that you don't start with a complex one-on-one digital twin with all the details in it and start with pilots on a smaller scale.

8. **Are you aware of any suppliers who can implement digital twins for your organization? Have you contacted them?**
   At least, I am not aware of any suppliers of digital twins as we have not reached that phase yet and we are still in the initial research phase. If I had to choose between developing a digital twin in-house versus going to vendors, I would first take the advice of my security colleagues of how we should work.

9. **What is the vision of your organization and how does it align with the adoption of digital twins?**
   I am not sure if I'm the right person to talk about his – I think our CEO should. But we want to deliver energy to our clients in an optimized way. And, if a digital twin can help us to do so, then it should align with our vision. Hard to say by when there will be large-scale adoption of digital twins in the energy sector – I would think 5-10 years. On a personal note, I do believe it is a great technology, but I don't think the entire energy sector will adopt it in 5-10 years, but a lot of companies will. You can also follow the adoption of BIM ('Bouw Informatie Management') because it has elements of a digital twins. BIM is about working together easier with other companies on projects and it's more from a building perspective.

10. **If the decision to implement digital twins in your organization today was solely in your hand, would you, do it?**
    If I know that the digital twin being offered is secure and does not have privacy issues, I may consider implementing digital twins. However, I would want to know more about the digital twin being offered. So, after I ask several questions to the vendor, I may consider digital twins.

INTERVIEW-6

Director at Large-Sized TSO/DSO

1. **A digital twin is a virtual replica of any physical asset. How does your organization see what a digital twin is?**
   I think a digital twin has been used as buzzword for quite some time as if it were something new. For example, our grid model is a digital twin of the exact live situation and we have been working with grid models since, computers started. So, you could state that digital twins have been there since computer-supported decision-making was possible. I think the digital twin in terms of using it non-synchronously to do maintenance work for example, is something new. I think that aspect of digital twin is related to the buzzword as we know it. We are working with offshore platforms – for which we have requested the contractor to also deliver a digital twin of the system when the platform was ready. This helped us in preparing activities without visiting the platform onsite upfront. So, a digital twin is a detailed enough model to do your maintenance work. The grid models that we have are not suitable to do maintenance. So, a digital twin is a new thing for the maintenance world, whereas, it has always been around in the system operations world. We have had distance-steering for our assets already for a longtime. In the 80s, we have built substations that we could monitor and steer on the most important components. Having people in the field who actually do the switching work on the substation was no longer possible and communication-wise, it's better to have a central operation center. Due to these operating centers, we have been able to monitor and steer components from a distance – so, this is nothing new to us that a digital twin can bring with it.

2. **In your opinion, what would be the potential digital twin use-cases for your organization?**
   As I mentioned, predictive maintenance is a clear use-case. Secure supply is also a use-case – the speed of electricity is 200k km/s and you can never be that quick even though we have all kinds of safety measures within our network. When it comes to decisions where the human factor is important and predicts the outcome of secure supply for safety, then we see a digital twin use-case. These require expensive systems because you need to have a direct communication line from your operating center towards your substation. These are physical assets, which costs money. We have balanced costs, performance and risks – and, we said it is worth it for us as a TSO, having an important role in Dutch economy and welfare that we try to steer what needs to be steered from a distance as good as possible. We can defend those costs as we are not a commercial company and are state-owned. Eventually, the tariff payer pays for the things we build and maintain. We can explain the investments to the tariff payer that it is in his/her interest that we do this.

3. **Why is your organization interested/motivated to consider investing in Digital Twins?**
   A Digital Twin supports one of our core values. We aim to go for secure supply and

having as little downtime as possible and this really supports us in that. In case an incident happens, or we need to redirect load flows, we can act almost instantaneously because we are 24/7 at the button. When people are at the substation, they would not be at the component itself – they would maybe leave their house, etc. and that costs time and that leads to a higher downtime.

4. **How far are you in the development of a twin / implemented digital twins in operations already? Why?**
A digital twin has a purpose and especially the level of a detail in a digital twin has a purpose. Because digitalization made it possible that we store and can manage huge amounts of information of our assets – slowly but surely, we did not speak about one model, but we have called it a digital twin. So, we digital twins of our offshore platforms – not all of them, but some of them have a digital twin and these were projects that started up in a time when sending and storing data back and forth was not so cheap as it is today. Some limited investments were done there – I am not in the maintenance department, but I learnt that the experience of a digital twin within the department were good. It does however mean that if you decide as a company to work with digital twins, you need to lay down a foundation for that – a data architecture, item designation and many other agreements as company not only with yourself but also with suppliers and the entire value chain about the language, the structure you use, the way you name things, etc. Only then digital twins are practical for use – it would not be a good idea if we have suppliers like ABB and siemens and we would ask them to come up with a digital twin and siemens would use structure A and ABB would use structure B. From their perspective, they are perfectly usable digital twins, but for us not – things will not be comparable for us. So, the eventual user (like us), have to set the standard and we are setting the standard at this moment – we work with BIM (Building Information Model), that delivers us eventually the digital twin and we have had our first pilot project already and we want to follow through and fully work with BIM as a company.

Apart from pilots, this structural implementation of the way of working with digital twins we are at step one out of four. Step-1 would be that you would prepare your company structures, step-2 setup standards in which you can make a digital twin, step-3 is then produce your digital twins and step-4 work with them. We are now laying down the foundation (step-1) which takes a lot of effort and is the most time-consuming step. But, if you have your foundation, step-2,3,4 follow-up quite easily. Before my current role in data management, I was responsible for asset management offshore, so we did a lot with offshore platforms in the Netherlands, and it was about 2018 when I first heard the buzzword term digital twin and the offshore pilot started in 2019. Back then, it was difficult to find parties who could do a pilot and deliver data in the structures we wanted to have (ISO19650 for BIM, I believe). We also wanted to not only have data in those structures, but we also wanted to be able to share our data with external supplier by using linked data. So, after the digital twin has been setup and you want to have some maintenance work done on a physical asset by an external party: you'd say here's my digital twin and I will now tender the maintenance work to this asset, I invite six suppliers to take a look at the digital twin and make their price based on the twin. And what is needed is that we are confident that this is a one-on-one digital twin of the asset and not something that is not, then there would be all kinds of change requests from the supplier which would be more expensive.

5. **How could you describe the (potential) impact of digital twins on your existing company processes/applications?**
   If I can summarize the impact of digital twin pilots so far, it led to local euphoria – wow, this is cool! (it's a cool play tool). On a company level, it does not add any value unless it is standardized, if you can scale this. I think the scalability of the digital twin is key in the success of it. If you cannot scale it and you have 100 digital twins and you have several different structures and languages, then you lose a lot of money in storing and maintaining that data and you do not gain anything of it.

6. **What are your thoughts on the risks and benefits of digital twins? Given equal risks and benefits, would you or not take the decision to use them?**
   I would see a couple of risks. One would be that if we fully trust on this digital twin 24/7 and we don't have a back-up like drawings for example and this is the high voltage grid (and is about electrical power). If the database that is dependent of electrical power does not work, then we don't have access to our assets, which would be terrible (we won't let that happen, but there's a risk in their when you trust your IT platforms too much). Secondly, I have learnt from an architecture book (it's a Dutch saying: Gelijk is Ongelijk', which means equal is off). So, if you have a white door and you want to have another white door in this room, you say I'll just go to the shop and buy white, you will always see a color difference. So, you need to buy the exact same paint for the two doors, so they are the same color (if you don't and there's a time difference, it's always off). Likewise, if you'd say I have a digital twin of a platform and I clicked the digital twin just before it was finished, I have some difference and this difference could mean only the difference between the two pots of paint (so to say) or it could also mean the difference of having a functioning network versus an outage.
   So, you have to be really sure about the fully automized coupling between the reality and the model. Thirdly, you really need to be aware of what you will use the digital twin for – so, what is the added value of your digital twin, do you use it for the actual steering on the network (then the digital twin should be extremely accurate). If use it only for doing your maintenance work, you can put less effort in deploying it as it still adds value because you can prepare your pre-maintenance tasks. The bottom-line risk would be that you are overly dependent of the digital twin – so, use it only for the intended application and not more than that. Also, you should setup your digital twin architecture in such a way that you are compliant with ISO27000 for example. These are architectural rules – if your design of your data model is good enough and compliant with these laws and there is no risk in data leaks/privacy issues whatsoever.

7. **In your opinion, what are the challenges to digital twin adoption in the Energy sector?**
For the TSO/DSO sector, a challenge is the regulation. If the regulator is not prepared for digitalizing TSOs and DSOs, that's a risk because often these (digital twins) are not capital expenditures, but operational expenditures. And operational expenditures are what regulators want to prevent. Then, there will be a paragraph in the new Dutch energy act stating that we need to share our data more – but this is only about data sharing (the way we get to the data) not about digital twins. For the rest of the sector: for offshore we can make a business-case of having a digital twin because the alternative is to fly there more often by helicopters – endangering our people and is quite expensive. When it comes to onshore substations, the business case is harder to make – some TSO/DSOs make ask why to invest in an expensive digital twin if you can go there by car and the drawings are in the substation (we don't have to be 24/7 on our onshore substation). So, for digital twin adoption in the entire sector, that's a limiting factor there. I think, shortage of people or more lower costs of these digital twins would be drivers of using them.

8. **Are you aware of any suppliers who can implement digital twins for your organization? Have you contacted them?**
Apart from ABB and IBM like I mentioned already. For digital twins right now that we are considering the Netherlands, we also hire external companies to do that for us. Most of the times, these are not the original contractors because these are existing assets. In the contracts that we still need to tender, we implement that the contractor needs to deliver a digital twin according to the standards and we have those standard right now (like I described step-1 out of 4). So, that means all new assets will be compliant with our standards. In that sense, the implementation is being done by an external party, but you still have to do with legacy data. Our assets have a lifespan between 20 to 60 years – before we have renewed our whole asset base, we are in 2081, for example. So, we need to figure out how we can make a digital twin on the existing assets because there is no contractor or supplier that knows how to do that - here we use 3D scans and ground radar to see what's underground. We are implementing an asset repository system in which we can store all our data in the correct structure which should be ready mid-next year. So, we can not only receive the models, but also use them which is also coupled with data from our existing GIS systems. We do have a contract with a vendor for our asset repository and that is to be finished next year. But, when it comes to digital twins of the individual assets, I think we will use multiple vendors because we are not completely sure in what order we would like to do stuff, how much work it would be – so, there's some insecurities about how much work and time, it'd cost. Being a state-owned company, we need to follow EU tender rules and that means we cannot just pick a party, we need to tender it always.

9. **What is the vision of your organization and how does it align with the adoption of digital twins?**
Our vision on digitalization is that it needs to support our challenges. Our challenges currently are that we see an enormous growth in new forms of energy –

offshore windfarms, onshore PV farms, etc. We see a lot of work coming towards us to connect all these parties and much more stuff is electrified today, and we will be lesser dependent on gas in the future. This means, we need to do a lot of investments as a company in digitalization. So, we need to do things smarter – we need to let smart systems work and thing for us, so we can do the really difficult (or maybe the fun) stuff. In the future, I do see digital twins widely adopted in our offshore activities and slowly, but surely see it adopted in our onshore activities and that will cost another 10 years before we have fully integrated it. Having a digital twin does not mean that all your work processes are integrated to get the maximum out of the digital twin – digitalization is a culture change.

10. **If the decision to implement digital twins in your organization today was solely in your hand, would you, do it?**
    Digital twins have a real promise, so I would say, yes – but then I'd manage the expectations that it will not be there next year and will take us another 10 years.

INTERVIEW-7
Director at small-sized TSO/DSO

1. **A digital twin is a virtual replica of any physical asset. How does your organization see what a digital twin is?**
   A digital twin is indeed a virtual copy of a physical asset – I agree with your definition.

2. **In your opinion, what would be the potential digital twin use-cases for your organization?**
   Yes, I see Predictive maintenance as a use-case. Other than that, we are a transporter of energy, so we use data to predict the capacity/volume of capacity we want to transport. If we would have data that signals to us that the peak capacity is rising, then that could help us replace or enlarge the capacity earlier than we may have had if we look at it generally. With real-time data from digital twins, you can make more precise decisions than you would with data which is generalized over the years. If you look at the real-time data, it could be that there are certain moments in time where the peak demand is much higher than expected and maybe then you'd invest in maintenance of capacity enlargement earlier than you would if you look at the generalized broader year data – demand forecasting is also an important use-case. As an asset-owner, the most important thing for me is to have my assets working optimally and I want to have them work for me for as little money as possible, but as good as possible. Predictive maintenance is one of the options to save money and do as much as you can by performing asset maintenance at the right moment, not too much and not too little. At the moment, we perform asset maintenance more based on trends and yearly policies. But the replacement of assets due to the energy transitions asks for us to be more flexible and the demand is rising more steeper than we expected – and I think more data can help you predict where to invest. If I know more about my asset and able to predict the demand and supply, I can make better decisions. Right now, we have not implemented digital twins, but made data lakes and used data scientists to get more data/knowledge of our assets.

3. **Why is your organization interested/motivated to consider investing in Digital Twins?**
   We have a lot of assets, and we have asset management systems which are based on ISO55001 and we use that to do things like risk management and security management. Where a digital twin can help us in is by simulating certain scenarios on your assets and you could check if predictive maintenance could help and if assets are working at their optimal capacity. Currently, we can only look at the physical versions of our assets because we do not have digital twins yet as far as some other companies have taken that step. But we do have a lot of data and the step that we are taking right now is more based on the data out of that physical asset and checking if we could optimize for example maintenance or replacement decisions. The main factors to optimize these maintenance and replacement decisions are of course, money – you can optimize the amount spent. What we do now: we do regular inspections of our assets, most of them each year. Based on the information

from the inspections, we make our maintenance program and replacement decisions. We base our investments on inspections and the general information (e.g.: life-cycle of the asset). But, by having digital twins of your assets, you don't need as many inspections, and you don't have to use general information to make the decision to replace something. That allows us to save money and almost most importantly, it allows us to save capacity, people, time hours (which is important as we have shortage of specialists at the moment. So, we want to use our specialists as best as we can and by having more knowledge of our assets we can make better decisions, cheaper and quicker. I think quality is also important, but the main drivers are money and capacity/human resources.

4. **How far are you in the development of a twin / implemented digital twins in operations already? Why?**
   On a scale of 1 to 10, let's say it's not a 1. We have been busy with the concept and have been talking to people to look into the possibilities. Many of our assets are 10,20, 30 years old, what we try to do is to deploy some sensor where our assets are located. Sometimes that could be in the surroundings of the building or on the transformer, but there are still not a lot of assets that you can buy off the shelf at this moment which create instantly a digital twin. I think that the big turnaround could be that the producers are going to create more transformers and their digital twins as well. So, that you just have to buy and install the physical asset (transformer) and you could immediately see the digital twin popping up on your screen – but that's still not the case. However, there is a problem there – the producer says I'm not going to do this because you don't ask for it. For example, if we want to buy the transformer, we ask the producer to give us the best price/option and the best option are cheap and maybe they will say something about the sustainability of the transformer, but they won't say anything about the digital side. Mostly likely, producers won't offer that because it is expensive, and they are afraid that the transformers will not be sold if they make it too expensive. The first time, I heard about digital twin was around 2-3 years ago in 2019 from a professor who wrote a book about it. For digital twins, we do not have any pilot projects in our company. Until now, we have only made data lakes, which is not the same as digital twins. We do have digital copies of our grid, for example with all kinds of data, but we don't have an exact copy of the asset.

5. **How could you describe the (potential) impact of digital twins on your existing company processes/applications?**
   If could have a digital twin of everything we have and make a virtual version of the outside world, it would mean that I could use it to make scenarios. At the moment, it takes a lot of time and energy to predict where the energy transition will take my assets. If we have a virtual version of everything, it will take you less time and you could to it over and over again and that would be helpful especially because the energy transition is happening so fast, and demand is growing fast. We as a DSO are behind the curve when it comes to digitalization relative to other DSOs. The information that we could get by having a digital twin would help us be more flexible – at the moment, we are behind not only because our assets do not have

any intelligence, but also because everything we have to compute at the moment is done by hand which is not sustainable as we are short on people. So, we have to become more proactive rather than reactive. At this moment we are reactive – the customer demands more, and we are trying to supply and meet the demand, but the reality is that we are only trying to catch up. And, if you want to get ahead, I think you need more information and digital twins could help.

6. **What are your thoughts on the risks and benefits of digital twins? Given equal risks and benefits, would you or not take the decision to use them?**
   As a grid operator, we have such strong regulations on cyber-security that to be honest, if we would have more data on our assets (from a digital twin), I would presume that would not be any additional risk to the (data) security of our grid. We have an IT and an OT network. Our OT network is very highly secure, and we get audited on that very regularly. To be honest, if there was any security risk now, it would not matter if we gathered more data from a digital twin. So, I do not see data security as a major risk. The highest risk is that if you have a digital twin, you perhaps think that it's the truth of the physical asset. You never go into the field again to inspect your assets and you overly trust your digital twin – I think that would be a risk. You have to continue validating what you see in your digital twin and not overly trust it. Another risk if digital twins are totally embraced, you could see that people may be willing to make more decisions from a distance (e.g., send an off signal to that asset). That would be risky because we are dealing with old assets and of course, digital information can help, but being solely dependent on it could have some risk. These risks are mitigable, but you need to think hard before you make decisions like that.

7. **In your opinion, what are the challenges to digital twin adoption in the Energy sector?**
   When I spoke with the professor, he told me that there are security companies on the other side of the world who can optimize data models based on the same data. In the end, one of the data models provided by the vendor could improve profitability of a DSO by 70%. What if we had a digital twin of the networks of all grid operators in the Netherlands – what if Eaton, Holec, ABB or one of the companies making transformers now had sensors in their assets? What if they can make a digital twin of the whole grid? What if they would tell us, they could make the grid better and safer for less money? The biggest challenge/risk for me us and other DSOs, is that these companies could potentially takeover our jobs and they could take care of the entire Dutch electricity grid and tackle issues like congestion, load balancing at a cheaper cost in a more efficient and reliable way. If Eaton, Holec and ABB, would have that information using sensors in their assets, they could then say to the government that we have now have a really good view of your grid operations and say make me the grid operator and I'll make it better for lesser money.

8. **Are you aware of any suppliers who can implement digital twins for your organization? Have you contacted them?**
   There are probably suppliers of digital twins out there. We have spoken to smaller

vendors that male GIS systems, but we have not contacted any supplier that provide digital twins. We are still in the research phase and have not reached the phase to contact suppliers yet – in fact, we did only a few research studies with a couple of university students.

9. **What is the vision of your organization and how does it align with the adoption of digital twins?**
For the coming few years, we have decided to invest in methods to better use the data we already have. I mean that we already collect a lot of data only to have it stored somewhere and we didn't do anything with it. So my first step was to better utilize the date we have – so, we are trying to analyze the data we have an build a use-case on that. Maybe we can use some predictive maintenance modeling on some of the data we already have. Perhaps, we may find that we lack certain amount of data, and we try to fill that gap. From that point of view, we are trying to fill the data lakes side of things. We are not building towards a digital twin system yet. I think that with more data on all our assets we will have a digital twin in the end within 10 years. What I see happening is that: we as a grid operator are being pushed towards uniformity and that wasn't the case until now (I could have a totally different maintenance and quality level from other DSOs until now). Adoption of Digital twins will push for this uniformity across the TSO/DSO sector in the Netherlands. I think the regulators will demand of us a certain amount of transparency on what we are investing in our grid. At the moment, we are getting away by just saying to the regulator: 'give us 100 million, and I will take care of it'. But, I think transparency expectations from the regulators and the public, will push us towards more data – digital twins, will help us show to them what we have in our grid and what levels we need to operate at. The reason why we have not yet had a digital twin pilot is because we are very small compared to other grid operators in the Netherlands, so we also have less resources in terms of money. So you see that in some innovations we are at the front, but for most of the innovations like the digital twin we have to leave to the bigger grid operators and try to serve along with what they are developing.

10. **If the decision to implement digital twins in your organization today was solely in your hand, would you, do it?**
I would say it depends, if I had unlimited amounts of capital and resources at my disposal, then yes. But given all the challenges we have; I try to the best I can with the people and the capital we have. And that's why I started with a data-lake option instead of a full-fledged digital twin.

INTERVIEW-8
Business Consultant at Large-sized TSO/DSO

1. **A digital twin is a virtual replica of any physical asset. How does your organization see what a digital twin is?**
   I did a year of research on this question alone. I heard you say the word 'visual' – I think that's one of the four possible options for a digital twin. There are four versions of digital twins that I see. First, you have the visual digital twins – you see these a lot in companies who focus on visual things (like designing companies). It's actually also the digital twin that has opportunities and that our company is looking into. A second type of digital twin is collection of data (e.g.: BIM companies which are usually trying to combine different collections of data on the same object, they also use SIM models for that). The third version is digital twins as an interactive model of assets, and I think this is the most common one when you look at large software companies like IBM when they talk about digital twins. The fourth one, (that I think is the most advanced and that I focused on) is digital twins as autonomous agents acting on behalf of a real thing. This concept gives every asset a real IP address and collects all the data that is available of this asset on that IP address and making this agent intelligent so that it could make its own conclusions on the available data. All these four different categories have their own maturity levels and their own benefits. Of course, I believe the last version is the most complex and you don't see a lot of people that are actually working on those. The last one also has to most value because if it works it will completely solve the problem of scattered data that is spread over different centralized systems that cannot be used if you don't access those systems. For example, in the energy sector, there can be 15 different companies that in the lifecycle generate and use data on the same assets and usually because its different companies all the valuable data stays in those companies and cannot be used in the entire lifecycle of that object.

2. **In your opinion, what would be the potential digital twin use-cases for your organization?**
   From the research I have done, I am convinced that the most value will lie in realizing the autonomous agent digital twin, but at the same time it is the most difficult for many reasons. One of those reasons is that it will make your data completely decentralized from big software companies. I believe, it is one of the reasons that digital twin does not develop because we have many well-paid software companies that don't really want us to get completely decentralized data. Visual Digital Twins and drone also has great opportunities especially because ML on visual inspections is growing very rapidly. If you think examples that are closer to realization and have great benefits, I think those are also very interesting. Still, one of the biggest problems in the energy sector is that there's all this important data scattered all over the place that is not available to everybody who needs it in the entire lifecycle – that's not something you solve with a model where you collect data too. The only way to solve that issue is with a digital twin.

3. **Why is your organization interested/motivated to consider investing in Digital Twins?**

Like I said, digital twins completely solve the problem of finding data of an object. This will make it possible to go to your digital twin and select it via the way you like. In my organization, we focused on our maintenance engineers and asked them: what way would you like to interact with the digital twin data? And they are familiar with 2D schemes of stations. What we worked on was a prototype that they can use to zoom on the schemes that they can use, and we would make it clickable, and they could see all the data that is collected on this subject. Even more, it could be possible to train this digital twin with AI that when maintenance engineers conclude something on this data today, the digital twin will show a warning/alert when the incident occurs again in the future. This has great opportunities when all the TSO/DSO work together. For example, we showed this model to another TSO/DSO, they were interested in it because this way they could see if something was going on in their energy network that they should be aware of. In the HV energy systems, you have this manual hook that you put on objects that is in maintenance – so, we were working on an idea that when you do out this hook on the physical asset, the digital twin sees this, and this is digitalized, and everyone can see this virtually instead of physically having to be there. Besides this, there are several departments in our organization that have their own interest in a digital twin. For example, the power line department is looking into an initiative that scan all the HV lines with a drone via photos and point clouds (LiDAR technology). This way you get a high-quality visual model of the power lines using ML and AI. You can further train this model for aspects that are relevant to your inspection planning. This is a completely different form of a digital twin which is a visual model, which also has great opportunities for our organization. Then you also have other departments that are busy with sensor data, if you ask them, they feel digital twins are more in line to an interactive model and what they are looking for how to make conclusions of all the sensor data that we collect.

4. **How far are you in the development of a twin / implemented digital twins in operations already? Why?**
   On a scale of where we are and what's possible (1 to 10), I think we are at 1.5. Maybe some companies are at 3, but I think there are many opportunities to uncover. We have conducted several pilot projects already. For example, object recognition with a visual model and last year we developed this very rapidly. Another pilot we are doing is on LV systems that have a temperature sensor and based on that it can decide on its own how much voltage is possible to transport. Until now, we did that manually, but it has been automated with the digital twin.

5. **How could you describe the (potential) impact of digital twins on your existing company processes/applications?**
   One of the potential impacts of digital twins in our organization was to automate the existing processes. Another pilot that we did was for maintenance engineers to collect data via the scheme that they use. This also had a lot of potential, but you are limited to the type of data suitable to a specific model. The maintenance engineers were happy with it, but on a certain level you have different object definitions, and you can't go further until you agree on those definition. We did an-

other pilot with object recognition and that was interesting for engineers in the designing phase. So, we scanned the location with LIDAR and based on the point clouds, the digital twin model suggests which model it is and that way an engineer can rapidly design the 3D model. So, if there's corrosion on a HV powerline, its concluded by the model that there's maintenance needed.

6. **What are your thoughts on the risks and benefits of digital twins? Given equal risks and benefits, would you or not take the decision to use them?**
Data security is certainly one of the risks a lot of people see when you start such pilots. On the other hand, when people use the fourth version of Digital Twin that I talked about earlier (with the IP address), we could also use security measures/technologies that people don't use in their organizations right now, for example, blockchain to safeguard your data. Doing so would actual secure the data even more than we do now because now we just create firewalls around our data. So, data security completely depends on how you design your digital twin. The risks also depend on which technologies you will use in the digital twin. For example, if you use ML in your digital twin model, you have to think of the risk of false positives and false negatives. In a pilot to recognize the electricity meter, we saw especially in the beginning that you will get a lot of false positives and negatives – our model recognized a modem as an electricity meter. So, if your models draw a conclusion of a false positive/negative that is dangerous then it could hamper the proper functioning of the grid.

7. **In your opinion, what are the challenges to digital twin adoption in the Energy sector?**
One of the main drivers of digital twins are the enormous challenges we face in the energy transition. For example, a TSO/DSO I know, is investing a lot of money into linked data, more system engineering stuff. From a technical perspective, the challenge is actually getting consensus on the name of objects and the codes that you assign and share data of objects (assets) between companies. On the other hand, most companies fear sharing data and what would this mean that for example a TSO/DSO can access all the data of an object owned by another TSO/DSO – this, could lead to a conflict in business models across the entire energy sector. So, the only driver to get digital twins realized is that people seeing if we don't do it, we won't get the job done towards energy transition. So, advanced digital twins (type-4 like I mentioned) face a lot of challenges like these. Business models of companies in the energy sector might have to completely be redesigned to function with advanced digital twins that shares data with everyone.

8. **Are you aware of any suppliers who can implement digital twins for your organization? Have you contacted them?**
With two of my colleagues, we actually visited the large software companies who offer digital twins. What we saw is that you should be aware of vendor bias – usually, these companies try to lock you in their software, and they would like you to buy their next software suite, etc. They feared the digital twin that I was working on because that would make them lose this vendor lock-in. You see that visual models are only available via their online platforms, and you can only access the data as

long as you pay the fees for it. I don't find the digital twins of these large software vendors to be very advanced, even though, they say that they have digital twins. The people that work on advanced digital twins are usually smaller companies – they are not only advanced for the energy sector, but in general.

9. **What is the vision of your organization and how does it align with the adoption of digital twins?**
   On all the four versions of digital twins, there is great enthusiasm from our management and of course it helps if the digital twin is already developed somewhere. For instance, the visual digital twins are easier to have an understanding on that the ones that I've worked on (type 4: interactive ones). Our board is not clear even if they even what a digital twin as the discussions are so complex because of so many stakeholders that are involved. On the other hand, the visual models (type-1 digital twins that I talked about), which are lesser interactive are the ones people are looking into investing right now.

10. **If the decision to implement digital twins in your organization today was solely in your hand, would you, do it?**
    Yes, of course! The advanced digital twin (type 4) that I talked about, is one of the biggest solutions for the problems we face. It's a lot of inefficiency because we can't share data that is useful with all the companies involved in the entire lifecycle of assets.

APPENDIX-B

ORGANIZATIONAL ABSORPTIVE CAPACITY - QUESTIONNAIRE

The targeted questionnaire used in this study has been adapted from the study: 'A measure of absorptive capacity: Scale development and validation' by (Flatten et al., 2011). The questionnaire consists of 14 statements measuring organizational absorptive capacity across four dimensions: Acquisition, Assimilation, Transformation and Exploitation. Each statement was rated between (1-5) (Strongly Disagree, Somewhat Disagree, Neutral, Somewhat Agree, Strongly Agree). The statements are as follows:

- **Acquisition**
  Please specify to what extent your company uses external resources to obtain information (e.g., personal networks, consultants, seminars, internet, database, professional journals, academic publications, market research, regulations, and laws concerning environment/ technique/ health/ security): -

  1. The search for relevant information concerning our industry is every-day business in our company
  2. Our management motivates the employees to use information sources within our industry
  3. Our management expects that the employees deal with information beyond our industry

- **Assimilation**
  Please rate to what extent the following statements fit the communication structure in your company:

  1. In our company ideas and concepts are communicated cross-departmental
  2. Our management emphasizes cross-departmental support to solve problems
  3. In our company there is a quick information flow, e.g., if a business unit obtains important information it communicates this information promptly to all other business units or departments
  4. Our management demands periodical cross-departmental meetings to interchange new developments, problems, and achievements.

- **Transformation**
  Please specify to what extent the following statements fit the knowledge processing in your company:

  1. Our employees have the ability to structure and to use collected knowledge

2. Our employees are used to absorb new knowledge as well as to prepare it for further purposes and to make it available
3. Our employees successfully link existing knowledge with new insights.
4. Our employees are able to apply new knowledge in their practical work.

- **Exploitation**
  Please specify to what extent the following statements fit the commercial exploitation of new knowledge in your company (NB: Please think about all company divisions such as R&D, production, marketing, and accounting):

  1. Our management supports the development of prototypes
  2. Our company regularly reconsiders technologies and adapts them accordant to new knowledge.
  3. Our company has the ability to work more effective by adopting new technologies.

Note*- An organization is considered to have a high absorptive capacity in a given dimension (Acquisition, Assimilation, Transformation or Exploitation), if they mark Somewhat Agree or Strongly agree in majority of statements in the block. In other words, for an organization to be deemed as having high absorptive capacity, the participants have the following responses: -*

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- ***Acquisition:*** *2 out of 3 statements must have agree/strongly agree (2/3)*
- ***Assimilation:*** *3 out of 4 statements must have agree/strongly agree (3/4)*
- ***Transformation:*** *3 out of 4 statements must have agree/strongly agree (3/4)*
- ***Exploitation:*** *2 out of 3 statements must have agree/strongly agree (2/3)*

TSO/DSO	Awareness	Use-cases	Motivation	Dev. Stage	Impact	Risks	Sector challenges	Vendors	Vision	Imp. Decision
Large-sized with low budget-size and high grid-length	Static and Dynamic DTs	Demand forecasting; Predictive Maintenance – not sure more research	Op. benefits; Simulation & Training	Research phase (2019); no pilots yet	Expects to boost productivity	Security; Privacy not a risk; Over-reliance on DT	Scoping; Investment costs later; Culture	Unaware	-	May consider – more research needed on security
Large-sized with high budget-size and high grid-length	4 types: Visual, Data collection, Interactive, Autonomous	Agent based DTs; Predictive Maintenance; Depends on definition	Internal drivers; 3 perspectives: Field-worker, Engineer, Simulation	Pilot Phase (started 2017); Rejected by MT; Diff. objectives b/w Asset owners & service providers	Automation; Productivitity ; Increases hand-on time;	Lack of knowledge; Data security not a huge risk; 1 Tech. risk	MTs have limited understand ing;	Initially: IBM, Bentley Systems; Later: In-house	-	No – already rejected; Not a business priority
Large-sized TSO/DSO with low budget-size and low grid-length	Separate internal and network DTs	Demand forecasting; Predictive maintenance	External drivers; Operational Efficiency; Market Transparency	Pilot Phase (started 3 years ago)	Risk/Asset planning; Early to generalize impact	Security/Privacy risk for later; Not deploying affects op. license	Limited resoucres at some DSOs	In-house for now	-	Out of time

Figure 6.1: A. Digital Twin Perceptions of Dutch TSO/DSOs

TSO/DSO	Awareness	Use-cases	Motivation	Dev. Stage	Impact	Risks	Sector challenges	Vendors	Vision	Imp. Decision
Large-sized with high budget-size and low grid-length	Buzzword; Novel only in maintenance not operations	Predictive Maintenance; Secure supply	Supports core value; Reduces downtime	Pilot phase (2019)	Do not add value unless standardized	Security/privacy not a risk; Dependence on DTs; Limited Scoping	Regulators – want to avoid op. ex; Some use-cases are not convincing	ABB; IBM; Multiple vendors	-	Yes, 10 years to fully integrate in operations
Small-sized with high budget-size and high grid-length	Agreed with definition	Predictive maintenance; Demand forecasting	Saves resources; costs; time hours; labor	No pilots; Limited resoures	Flexibility; Help match demand	Cybersecurity not a risk; Dependence on DTs	DT vendors can take over their business	Unaware	-	Not sure – high investments/ resources required
Small-sized with high budget-size and low grid-length	Limited knowledge	Limited knowledge	Limited knowledge	Limited knowledge	Limited knowledge	Limited knowledge	Limited knowledge	Limited knowledg e	Limited knowle dge	Limited knowledge

Figure 6.2: B. Digital Twin Perceptions of Dutch TSO/DSOs

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