# TOWARDS OPTIMISED POWER DISTRIBUTION: EXPLORING THE SYSTEM SAFETY OF DIGITAL TWINS

A holistic approach to establish a system safety framework for the implementation and operation of Digital Twins in power grid optimisation

TU Delft accenture

# Towards Optimised Power Distribution: Exploring the System Safety of Digital Twins

A holistic approach to establish a system safety framework for the implementation and operation of Digital Twins in power grid optimisation

By

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# Preface

As I reach the end of my Master's journey in Complex Systems Engineering and Management at Delft University of Technology, I am excited to present this thesis. Writing it has been a challenging yet incredibly rewarding experience, diving into the world of Digital Twins and their role in optimising power distribution systems. This work explores the system safety of Digital Twins in power grids, a topic that is becoming increasingly important as we move towards smarter and more resilient electricity networks. By addressing the intersection of technology, policy, and management, I aim to contribute to the ongoing discussion on how to safely implement and operate Digital Twins, particularly within Distribution System Operators.

I am very grateful to everyone who supported me along the way. First, a huge thank you to my supervisor, Dr. ir. R.I.J. Dobbe. Our weekly conversations were a constant source of inspiration, and your enthusiasm for the topic was infectious. Your open mindset and guidance, especially in AI and system safety, provided new insights that significantly shaped this research. I also want to express my gratitude to my supervisor and chair Dr. ir. R.A. Hakvoort. Your clear feedback and vast knowledge of the electricity grid and the organisation of Distribution System Operators were really valuable. Your extensive research experience helped me structure my work more effectively.

I am incredibly thankful for the opportunity to write my thesis at Accenture. The inspiring environment, surrounded by experienced and passionate professionals, made me even more enthusiastic about my research. In particular, I would like to thank my supervisors Sven Feijen, Bart Geelen, and Piet-Jan Schipper. Sven, thank you for your weekly sessions and critical perspective. Your expertise in Complex Systems Engineering and Management and your ability to think through challenges with me were incredibly helpful. And of course, your impressive PowerPoint skills never ceased to amaze me. A big thank you to Bart Geelen and Piet-Jan Schipper. Your support in providing feedback, connecting me to experts in the field, forwarding relevant articles, and sharing your deep knowledge of Distribution System Operators and the electricity grid was essential. Your inspiration and practical insights greatly enriched this thesis.

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To everyone who has been part of this journey, thank you for your support and guidance. I hope this thesis will inspire others, just as all of you have inspired me throughout this process.

Janneke Bulkmans

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# Executive summary

The electricity grid is congested in many parts of the Netherlands, hindering businesses from connecting to the grid and potentially resulting in blackouts during peak hours (Ministerie van Algemene Zaken, 2023). Therefore, it is important to ensure sufficient grid capacity in the coming years. The adoption of Digital Twins (Digital Twins) within Distribution System Operators (DSOs) can contribute to mitigating grid congestion and improving the resilience of power distribution systems. Digital Twins are a virtual representation of physical assets within the grid, enabling real-time monitoring, analysis, and optimisation of network performance (Botín-Sanabria et al., 2022). By simulating various scenarios and predicting potential congestion, Digital Twins can help operators to manage grid operations and eventually prevent disruptions.

However, the existing literature reveals a significant knowledge gap in the adoption of Digital Twins within power distribution networks, particularly in the examination of socio-technical safety factors. System safety is a vital aspect to consider when implementing a complex system in critical infrastructure, such as the implementation of Digital Twin in the electricity grid. This research studies system safety from a socio-technical perspective because safety is an emergent feature of systems which can only be addressed in context with the system as a whole.

This study uses an exploratory qualitative research approach to investigate sociotechnical factors influencing the safe implementation and operation of Digital Twins in power distribution systems. The existing literature was reviewed systematically to identify and map various system safety factors for different Digital Twin applications. The literature review is described in chapter 3.

Several, primarily technical, system safety factors emerge from this study. Firstly, system safety factors related to the model performance are identified. The model performance relates mainly to the accuracy models to describe (physical/real-world processes). Secondly, factors related to the data quality are identified, (including the use of incorrect data and impact of data volume on system performance). Thirdly, it becomes apparent that real-world conditions are often not fully considered, and the models have yet to be tested under these conditions. Finally, the importance of using quality standards for different Digital Twin components is emphasised.

Following the identification of system safety factors in literature, desk research and interview are conducted, as described in chapter 4. To get a holistic view of the safety regarding the implementation and operation of a Digital Twin within a Dutch DSO, the desk research and interviews are approached from technical, institutional and process perspectives. The desk research provides a general overview of current systems, processes, regulations, organisational structures and involved processes and stakeholders within a Dutch DSO. The process perspective is analysed by mapping the relevant roles and interactions of different stakeholders as well as within DSOs, regarding the implementation and operation of a Digital Twin. Relevant controls, rules and laws are displayed in a formal chart during the institutional analysis, to see how these institutional factors influence operations within a DSO and stimulate safety (Enserink et al., 2022). The technical systems, processes, controls, and data flows are represented in a framework during the technical conceptualisation. These different components of the desk research serve as a foundation for the interviews and the framework.

To find out how specific technical, institutional and process-related factors related to the application of Digital Twins for DSOs in the Netherlands affect system safety, the opportunities and challenges are first identified through interviews. Nine interviews are conducted, including six people working at two different DSOs in the Netherlands, and three experts in the field of Digital Twins in the electricity sector. The most important technical factors that emerge from the interviews are system integration, data quality and integrity, data integration, and technical complexity. The interviewees also identify several regulatory challenges to consider. Factors that emerge regarding the design, implementation and maintenance process of the Digital Twin are the development approach, collaboration within DSOs and collaboration with other stakeholders.

The technical, institutional and process components from the desk research, along with the socio-technical factors identified in the literature research and interviews, are structured into a framework in chapter 5. The framework is in the shape of a safety control structure and has been established by using a System-Theoretic Process Analysis (STPA) inspired approach (Leveson & Thomas, 2018). Performing this analysis, system safety aspects can be structured by identifying loss scenarios, potential hazards, unsafe control actions and finally constraints within this complex system. The loss scenarios are undesirable scenarios, which are based on the factors identified in the literature review and the interviews. From here, it is investigated how the loss scenarios can lead to unsafe control actions and system-level hazards. In this way, it is examined how the identified socio-technical aspects can affect the safety of the grid at system level. To guarantee the system safety of the grid and the people around it, with regard to the implementation and operation of the Digital Twin, safety constraints are ultimately drawn up and incorporated into the safety control structure (Figure 9).

In conclusion, this study provides the socio-technical factors influencing the safe implementation and operation of Digital Twins in the power distribution sector. The proposed framework, a safety control structure, serves as a guide for DSOs to assist them in a safe implementation and operation of Digital Twins. This research addresses the knowledge gap of a holistic approach to the safe implementation and operation of Digital Twins for DSOs. Moreover, this study shows how an STPA-inspired analysis can be used to analyse and enhance the system safety of AI models.

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# List of abbreviations

| | |
|---|---|
| **DSO** | Distribution System Operator |
| **TSO** | Transmission System Operator |
| **PV** | Photovoltaic |
| **IT** | Information Technology |
| **OT** | Operational Technology |
| **NDA** | Non-Disclosure Agreement |
| **IEC** | International Electrotechnical Commission |
| **NIS2** | Network and Information Security (Directive) |
| **NTA 8120** | Dutch Technical Agreement 8120 |
| **GDPR** | General Data Protection Regulation |
| **AI** | Artificial Intelligence |
| **NWO** | Dutch Research Council (Nederlandse Organisatie voor Wetenschappelijk Onderzoek) |
| **EMS** | Energy Management System |
| **DMS** | Distribution Management System |
| **GIS** | Geographic Information System |
| **SCADA** | Supervisory Control and Data Acquisition |
| **OC** | Operating Centre |
| **LS** | Loss Scenario |
| **UCA** | Unsafe Control Action |
| **STPA** | System-Theoretic Process Analysis |
| **CoSEM** | Complex Systems Engineering and Management |

# 1 Introduction

## 1.1 Background: Relevance of Digital Twins

The power grid is congested in many parts of the Netherlands, which will complicate connecting businesses and customers to the grid in the upcoming years (Ministerie van Algemene Zaken, 2023). Due to the uptake of renewable energy sources, such as solar photovoltaic (PV) and wind, as well as demand electrification, both supply and demand of electricity are putting stress on the current electricity infrastructure, exceeding the technical grid limits (Ministerie van Algemene Zaken, 2023). The supply and demand for electricity are increasing faster than the capacity of the grid to grow. Therefore, measures are needed to ensure sufficient grid capacity in the coming years. According to the Ministry of General Affairs (2023), failing to address this issue could lead to overloading the grid. This, in turn, could potentially result in blackouts as well as customers not being able to connect to the electricity grid (for both consuming and generating electricity). Consequently, grid congestion is a challenge to the efficient operation of power distribution networks, threatening the optimal and dependable electricity distribution.

However, Digital Twins might be able to help reducing grid congestion and improving the resilience of the electricity grid. Digital Twins are virtual representations of physical assets within the grid, which enable real-time monitoring, scenario analysis, and optimisation of network performance (Botín-Sanabria et al., 2022). By simulating various scenarios and predicting potential congestion, Digital Twins can help operators to manage grid operations and prevent disruptions. Besides that, using virtual grid modelling, it is frequently discovered that additional space exists behind the connection, so there is no need for a larger grid connection (Van Vlerken, 2024). It is important to investigate the application of Digital Twins in this sector because a Digital Twin can accelerate the process of solving these types of complex infrastructure issues (Palensky, 2023). It is important to explore and analyse different applications of Digital Twins specifically designed for power distribution grids to fully use the capabilities of Digital Twins in mitigating grid congestion.

Studying how to implement Digital Twins to reduce grid congestion has significant societal relevance due to its potential impact on society. It is critical for businesses, households, and essential services, to ensure reliable access to the electricity grid, which in turn supports economic prosperity and public well-being. Addressing grid congestion issues can prevent potential blackouts, minimise power outages, and guarantee that communities receive uninterrupted electricity services (Ministerie van Algemene Zaken, 2023). Furthermore, the integration of renewable energy sources and lowering carbon emissions can be supported by optimising power distribution networks with technologies like Digital Twins.

## 1.2 Literature review

A systematic literature review is first conducted to explore existing studies on Digital Twins in the context of power grids. The review aimed to identify the current state of knowledge, focusing on the implementation and operation of Digital Twins within power distribution networks, with a particular emphasis on system safety. Based on this literature review, a knowledge gap is identified, from which the research question is formulated.

### 1.2.1 Literature review method

The literature review was conducted to explore what research has previously been studied regarding Digital Twins for power grids, with a focus on system safety. According to Page et al. (2021), clearly defining the criteria to determine what information was eligible or ineligible should allow readers to comprehend the scope of the review and confirm inclusion selections. The inclusion criteria of this systematic literature review are:

1. Year of dissemination is starting in 2018.
2. Language is English.
3. The article must be open accessible.
4. The article should be about Digital Twins for power distribution.
5. The search was conducted using the following query: (*"digital twin" OR "digital twins" OR "digital twinning" OR twin ) AND ( dso OR "distribution system operator" OR distributor OR distribution OR distributed OR grid ) AND ( power OR electricity OR electrical* ).

Performing the search query yielded sixteen articles that were open accessible. One article of these was excluded as it was published before the year 2018. Another article was excluded because it concerned a Digital Twin for power distribution system of a civil aircraft, and thus did not meet criterion four. It is important to note that a search string without a keyword related to system safety was chosen as this did not yield any search results. The articles analysed in the literature review have been structurally ordered in *Appendix A: Literature review findings*. The table lists the type of Digital Twin discussed in the literature and the social and scientific relevance of this Digital Twin with respect to power distribution.

### 1.2.2 Digital Twins in literature

Digital Twins have been increasingly recognised as a relevant tool for optimising power distribution networks. They are virtual models of physical systems that can simulate and predict system behaviour, enhancing decision-making processes for DSOs. However, while Digital Twins offer potential for optimisation, they also introduce new complexities that can impact the safety of the grid. Decisions based on Digital Twin simulations and predictions may carry risks, especially if the models do not accurately reflect real-world conditions or if socio-technical factors are overlooked. Despite their growing relevance, the literature reveals gaps in understanding how Digital Twins should be implemented and operated, particularly regarding the integration of socio-technical factors alongside technical considerations, and how these factors influence system safety and the potential for hazards.

#### *1.2.2.1 Definition of a Digital Twin*

A Digital Twin is a virtual representation of a real-life process or object designed to gather data from the actual events to simulate current or potential behaviour of the physical twin (Botín-Sanabria et al., 2022). By using Digital Twins, users and stakeholders can gain an in-depth understanding of any system's internal operations, the interactions between its various components, and the potential behaviour of its real-world counterpart. According to research of Botín-Sanabria et al., (2022) Digital Twin is an emerging technology with a significant increase in case studies, most of which focus on predictive analysis and lifecycle management for a range of sectors and businesses.

#### *1.2.2.2 Knowledge gaps in the implementation and operation of Digital Twins*

Several Digital Twin applications can be found in the literature that aim to analyse and/or improve power distribution, as shown in *Appendix A: Literature review findings*. In addition, a variety of tools and techniques are also used for different applications in the power distribution sector. However, Bai and Wang (2022) claim that the digital power grid's properties and characteristics have not been thoroughly explained or described. Heluany and Gkioulos (2023) also conclude in their research that a consensus regarding the definition of the term "Digital Twin" is lacking. They indicate that definitions, applications, and tools across various layers of the Digital Twin still exhibit notable inconsistency. The literature therefore shows a lack of generalisation of the Digital Twin and its implementation and operation. Furthermore, while integrating the Digital Twin for distribution of power, external elements are often disregarded (Xie et al., 2019). Nasiri and Kavousi-Fard (2023), for instance, stress the significance of evaluating the network's cyber vulnerabilities in future research. Moutis and Alizadeh-Mousavi (2021) likewise conclude that the techniques should be evaluated in terms of interruption and installation expenses.

Tool quality and different image processes must be considered in order to make Digital Twin effectively applicable (Fernandes 2022). Additionally, the study by Heluany and Gkioulos (2023) suggests that future research could explore areas such as detailed architecture and framework, security measures, stakeholders, and network integration as potential subjects for investigating the implementation and operation of Digital Twins in power grids. The study also concludes that future research could emphasise proposing an architecture or framework that considers the specific demands of the power distribution sector. Moreover, the study by Bai and Wang (2022) stresses the need for a guideline in adopting a Digital Twin for a power grid.

While Digital Twins are recognised for their technical capabilities, there is a significant gap in the literature regarding their holistic implementation and operation, particularly in addressing the integration of socio-technical factors and ensuring system safety. Existing studies largely focus on the technical aspects of Digital Twins, such as model accuracy and data integration. However, these approaches often neglect the broader socio-technical context in which Digital Twins operate. This includes the interaction between technical systems and organisational processes, regulatory frameworks, and human operators.

Moreover, the importance of system safety within this socio-technical context is often underexplored. Given that power distribution networks are critical infrastructures, any failure or disruption can have severe societal and economic impacts. Therefore, there is a need for research that not only addresses the technical implementation of Digital Twins but also integrates system safety considerations within a socio-technical framework.

#### *1.2.2.3 Importance of system safety*

The existing literature reveals significant knowledge gaps in the implementation and operation of Digital Twins within power distribution networks, particularly in the examination of socio-technical factors. This knowledge gap can potentially lead to vulnerabilities in system safety. According to Leveson (2023) the complexity of systems nowadays is growing exponentially, making them orders of magnitude more complex than they were in the past. Additionally, system safety is an emergent property of complex systems, arising from the interactions between various components (Leveson, 2023). In the context of Digital Twins for power distribution, ensuring system safety requires a comprehensive approach that considers both technical and socio-technical factors. The complexity of modern power grids, combined with the introduction of Digital Twins, necessitates a framework that can manage these interactions to prevent accidents and losses. Moreover, system safety is crucial for a critical infrastructure like the electricity grid, because any failure or disruption can lead to societal and economic impacts.

### 1.2.3 Research question

The absence of a consistent and comprehensive framework for adopting Digital Twins, as highlighted by Bai and Wang (2022) and Heluany and Gkioulos (2023), indicates a need to develop guidelines that consider both social and technical dimensions. This research addresses this gap by focusing on unaddressed socio-technical factors to develop a structured approach for the safe implementation and operation of Digital Twins in power distribution networks. Therefore, the main research question states:

*What are the key system safety factors for a Distribution System Operator to consider for the implementation and operation of a Digital Twin?*

This research question directly addresses the knowledge gap by contributing to the development of a holistic framework for the safe implementation and operation of Digital Twins in the power distribution sector. This framework aims to unify social and technical aspects, tackling the broader challenge of ensuring system safety and operational reliability. Ultimately, the goal is to standardise Digital Twin implementation and operation practices across the industry, maximising their benefits while safeguarding the power grid's safety.

# 2 Methodology

## 2.1 Introduction to methodology

This study uses an exploratory qualitative research approach to thoroughly investigate key technological, institutional, and process-related factors influencing the safe implementation and operation of Digital Twins in power distribution systems. An exploratory qualitative research approach allows for the discovery of concepts and perspectives that have not been considered before, which contributes to the development of a conceptual framework (Dudovskiy, n.d.). A full overview of the research flow can be found in Figure 1.

The main research question is:
*What are the key system safety factors for a Distribution System Operator to consider for the implementation and operation of a Digital Twin?*

The sub-questions that have been established to answer the main research question are as follows:

1. *Which system safety factors have been considered for different applications of Digital Twins in electricity distribution, from a socio-technical perspective?*
2. *What are the related socio-technical opportunities and challenges associated with the implementation and operation of Digital Twins for Distribution System Operators in the Netherlands?*
3. *How do the identified factors associated with the implementation and operation of Digital Twins affect the system safety of the grid?*

These questions are examined inductively. In fact, during an inductive investigation, it is examined how results can be generalised based on specific observations (Benders, 2022). According to Benders (2022), an inductive investigation consists of the following four steps: making an observation (lack of socio-technical system safety aspects), collecting data (literature review and interviews), discovering a pattern (coding) and formulating theory (framework). The following sections explain the rationale behind these sub-questions. In addition, it is explained how the data is obtained and analysed and what the specific requirements are. In the discussion of this study, the limitations of the chosen methods are explained. The limitations of the methods chosen for this study are described in chapter 6.

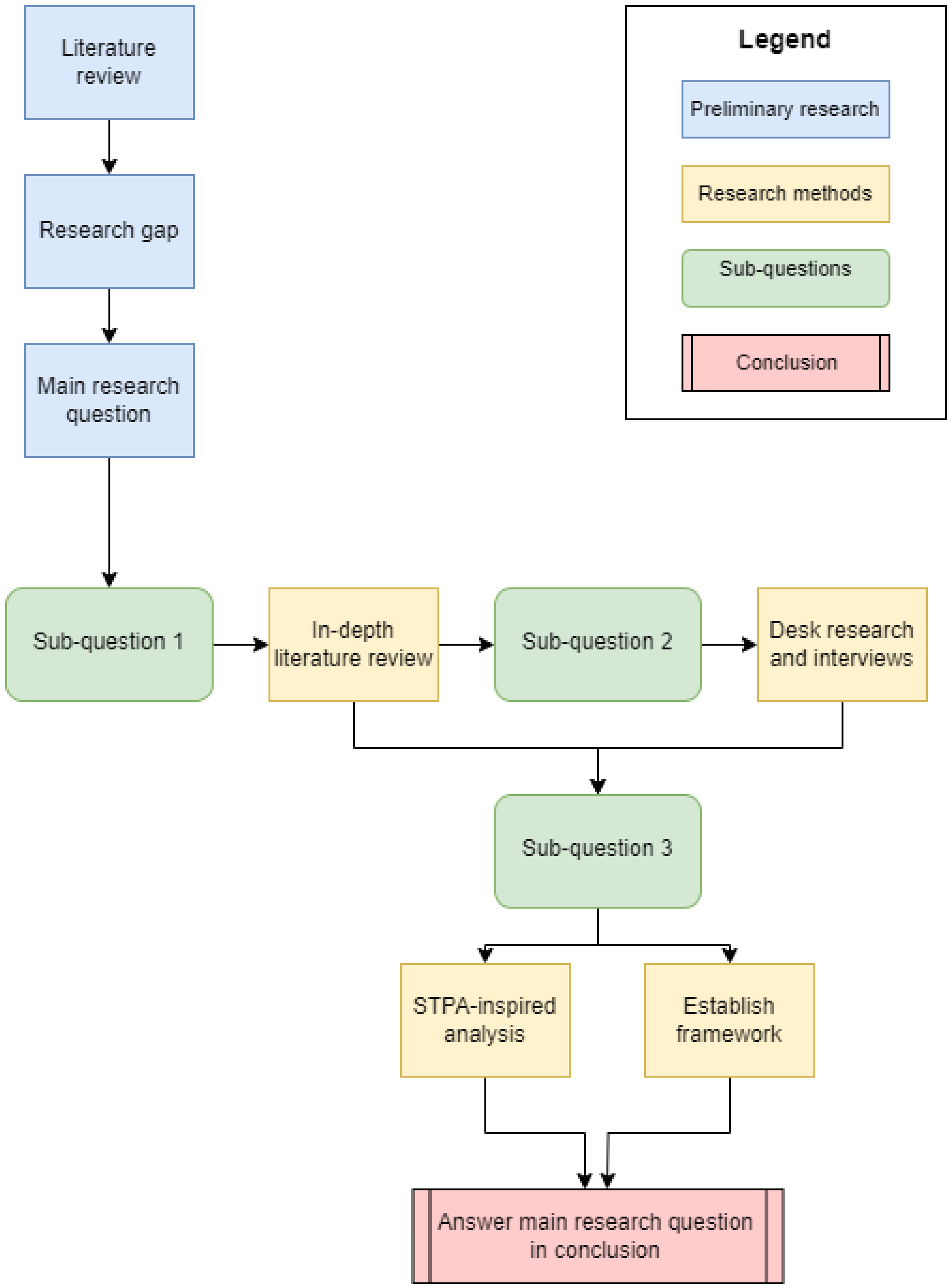


*Figure 1: Research Flow Diagram*

## 2.2 Sub-question 1: In-depth literature research

The first sub-question states:

1. *Which system safety factors have been considered for different applications of Digital Twins in electricity distribution, from a socio-technical perspective?*

This sub-question is answered by conducting an in-depth literature review. According to Snyder (2019), literature research can be used to understand overlapping themes, to bring together research findings and to reveal what is known and what needs more study. The literature review involves using citation management tools like Mendeley to organise and manage references. All Digital Twin applications from the literature must be employed since 2018, to collect current and reliable results and avoid using outdated information (Scharwächter, 2022). Literature is considered relevant when it contains an application regarding Digital Twins for power distribution grids.

The same search query is used as in the previous literature review, using different inclusion criteria. Within the literature research, the system safety features for the implementation and operation of Digital Twins for power grids are mapped, analysing different Digital Twin applications. Although it has already been noted that few socio-technical features have been identified in the literature, it is important to map and analyse them in-depth. This helps to get a holistic overview and to provide a foundation for the interviews and the final framework. This is done to gain insight into potential features that are important for the safe implementation of Digital Twins in the power distribution sector, as well as to identify any challenges and opportunities.

According to Page et al. (2021), clearly defining the criteria to determine what information was eligible or ineligible should allow readers to comprehend the scope of the review and confirm inclusion selections. The inclusion and exclusion criteria can be found in Table 1 below.

*Table 1: Inclusion and exclusion criteria*

| Inclusion criteria | Exclusion criteria |
|---|---|
| 1. Year of dissemination is starting in 2018. | 1. Language is not English. |
| 2. The article should describe a Digital Twin application for power distribution. | 2. The article is not open accessible |

The search is conducted using a search query on Scopus. The keywords are chosen based on a study of the different terms of the concepts. A search query with terms to appear in the title is chosen because it was discovered that Digital Twins are often referred to in the abstract without delving into the content.

The search is conducted using the following query:

> *TITLE ( ( "digital twin" OR "digital twins" OR "digital twinning" OR twin ) AND ( dso OR "distribution system operator" OR distributor OR distribution OR distributed OR grid ) AND ( power OR electricity OR electrical ) ) AND PUBYEAR > 2018.*

The search query yields 16 articles that are open accessible. Three other articles are not included because they do not describe a specific Digital Twin application for power distribution, and thus do not meet inclusion criteria two. Relevant information about the safety of the electricity grid regarding the implementation of Digital Twins is selected by searching for various keywords that address system safety within the articles. This literature research method is based on the grounded theory of Glaser and Strauss (1967). The objective of this approach is to explore the specific (safety-related) terms to finally reveal the different categories of system safety that have been considered in the publications. The list of system safety keywords is drawn up iteratively by reading multiple publications about system safety in various domains. After this, several variations of words are created (such as dependence and dependent) to ensure that no similar words are skipped.

Identified system safety keywords:

- *Safety*
- *Risk*
- *Dependent*
- *Dependence*
- *Fault*
- *Challenge*
- *Accurate*
- *Reliability*
- *Vulnerability*
- *Precise*
- *Uncertain*
- *Problem*
- *Feasible*
- *Critical*
- *False*
- *Rules*
- *Regulation*
- *Regulatory*
- *Implication*

From here, the context surrounding these system safety keywords is extensively analysed, and categories are drawn up for the various overlapping socio-technical themes discussed around the safety of the Digital Twin. The coding is done manually and independently.

## 2.3 Sub-question 2: Desk research and interviews from three different perspectives

The second sub-question states:

2. *What are the related socio-technical opportunities and challenges associated with the implementation and operation of Digital Twins for Distribution System Operators in the Netherlands?*

To answer the second sub- question, desk research is first conducted to conceptualise the current Digital Twin system from a technical, institutional, and process-perspective and to serve as a foundation for the final framework. Then, semi-structured interviews are conducted to explore the current opportunities and challenges around system safety of Digital Twins within the power distribution sector. The interviews analyse the progress around Digital Twin implementation at two different DSOs. An interview is an appropriate research design to acquire contextual, specific, in-depth knowledge about a particular actual topic (McCombes, 2023).

To get a holistic perspective on the different system safety features of the implementation and operation of the Digital Twin, the desk research and interviews are approached holistically from three different angles: the technical perspective, the institutional perspective, and the process perspective (Bots & Van Daalen, 2012). This approach is used to finally design a holistic framework, based on the three different perspectives. Generally, the first perspective focuses on the technical implementation and operation of Digital Twins for the power grid. From the institutional perspective, the regulatory factors that influence Digital Twin implementation and operation are explored such as regulations and guidelines to which the Digital Twins and the power grid need to adhere. Through the process lens, the procedural and operational changes and implications induced by Digital Twins, with a particular emphasis on the roles, interests, and interactions of stakeholders, are investigated.

### 2.3.1 Desk research

Before the interview is conducted, desk research is conducted to identify existing technical, institutional and process-related Digital Twin concepts, related to Digital Twins within DSOs. Existing (government) reports and literature are used. The process perspective is approached by identifying the various stakeholders and their functions, interests and interactions. The several relevant teams and departments within a DSO are also outlined to understand cooperation and dependencies related to the implementation and operation of the Digital Twin. Next, the institutional conceptualisation involves the construction of the formal chart from Enserink et al. (2022). This is done to identify the various rules that ensure the system security of both the power grid and the Digital Twin. The system is then analysed technically by mapping the various technical components (systems, functionalities, data flows, etc.) relevant to a Digital Twin within a DSO.

### 2.3.2 Interviews

To ultimately answer the second sub-question, interviews are conducted with nine participants. According to Benders (2022a), eight to twenty respondents need to be interviewed when researching a heterogenous group of respondents to ensure theoretical saturation. Theoretical saturation occurs when the answers to interview questions no longer provide the researcher with new information: i.e., enough participants have been interviewed to make valid statements based on the interviews.

#### *2.3.2.1 Participant selection*

Nine participants were interviewed. Of these, three participants work at a technical department at a Dutch DSO and three participants work at a technical department at another Dutch DSO. The other three participants are Digital Twin experts, with knowledge and experience in the electricity domain. Because the knowledge and experience of the different participants overlap nine interviews are considered sufficient for the purpose of this interview. Additional information about the participants' experience can be found in *Appendix D: Summaries of interviews*.

Since an inductive research method is applied, different types of questions are asked (Benders, 2022b), as shown in Table 2. In this explorative research, questions are asked by means of a semi-structured interview. When using a semi-structured interview, some of the questions asked are determined prior to the interview (*Appendix B: Guiding questions semi-structured interview*). The order in which the questions are asked is flexible to ensure respondents can answer completely freely and the interviewer can ask further questions about the answers (Genau, 2023). After transcribing the interviews, Atlas.ti is used to code interview transcripts to identify recurring themes related to opportunities and challenges. Initially, a large number of codes is created to look into the themes that show up throughout multiple interviews. Then, overlapping codes are combined to form main themes (see chapter 4.3. for an explanation of these themes as opportunities and challenges).

*Table 2: Type of interview questions and purpose*

| Type of question | Purpose |
|---|---|
| Predictive questions | To gain insight into the further development of Digital Twins and its consequences |
| Evaluative and normative questions | To gain insight into the challenges regarding the safe development of Digital Twin |
| Design, problem-solving questions and advisory research questions | To gain insight into the opportunities regarding the safe development of Digital Twins |
| Explanatory questions | To determine the causes of problems or scenarios |

## 2.4 Sub-question 3: System safety framework

The last sub-question states:

3. *How do the identified factors associated with the implementation and operation of Digital Twins affect the system safety of the grid?*

The findings of the literature review, the desk research and the interviews are incorporated by means of a conceptual framework. This framework is established using the conceptual desk research as a foundation for the technical, institutional and process components of the structure. The results of the literature review and interviews are then analysed using a System-Theoretic Process Analysis (STPA)-inspired approach, adopted from Leveson and Thomas (2018), which is also incorporated into the framework. This provides a clear overview of how the technical, institutional, and process-related factors influence the system safety of the entire system. This safety control structure is intended to serve as a guiding tool for the safe implementation and operation of Digital Twins for DSOs in the Netherlands and ultimately answers the main research question. The exact application of the STPA-inspired is be explained step by step the following section.

### 2.4.1 STPA-inspired analysis

The method used to develop the safety control structure is based on the System-Theoretic Process Analysis (STPA) from Leveson and Thomas (2018). The steps of the original STPA are illustrated in *Appendix E: Original STPA-Structure*, where Leveson and Thomas (2018), first define the purpose of the analysis, then model the control structure and identify the unsafe control actions and controller constraints, and finally identify loss scenarios (Figure 2). However, the STPA-inspired analysis in this research, first defines the purpose of the analysis, then identifies the loss scenarios, unsafe control actions and controller constraints and finally models the safety control structure, as can be seen in Figure 3. Nevertheless, it is important to mention that the STPA analysis is an iterative process. The different parts of the STPA-inspired analysis are therefore not strictly performed in this order, but it can be used as a guideline to perform a similar analysis. The various steps and their logical sequence are described below. The traceability that is maintained between the outputs of the various

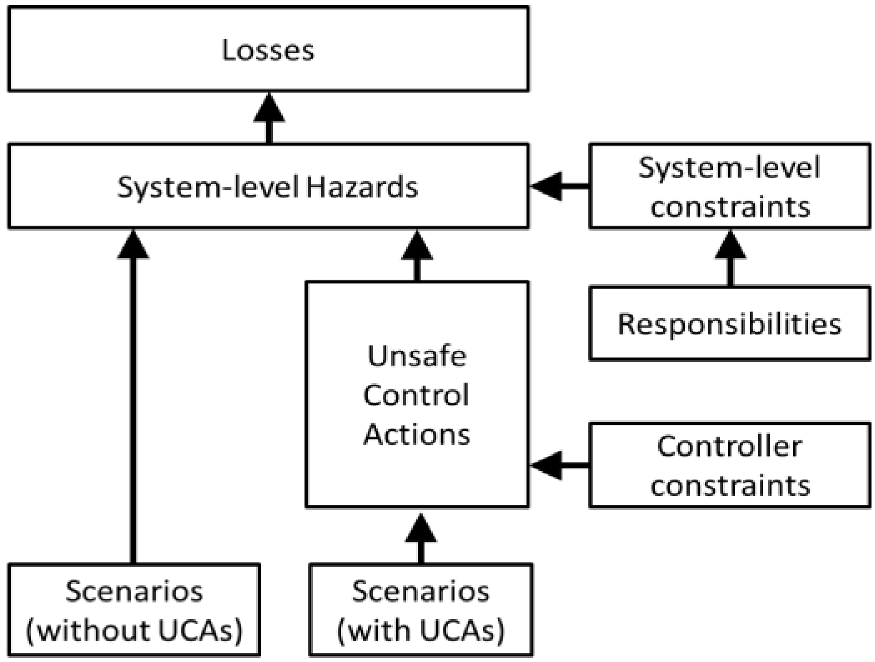


*Figure 2: Interdependencies STPA (Leveson & Thomas, 2018)*

steps of the analysis, can be found in Figure 2.

1. **Define purpose of analysis**

The first step is to define the purpose of the analysis, so what losses regarding the safety of the implementation and operation of Digital Twins the analysis will strive to prevent. This consists of two steps, namely to identify system-level hazards and to identify losses.

1.1. **Identify system-level hazards**: Determining the hazards associated with the development and application of the Digital Twin is the first step. According to Leveson and Thomas (2018), a hazard is a condition of a system, or a collection of circumstances that, when combined with a specific set of the worst possible environmental circumstances, will result in a loss.

1.2. **Identify losses**: To define the purpose, the potential losses of the system are identified, when implementing and operating Digital Twins within a DSO. The losses are the worst-case scenarios, resulting from the system-level hazards, which are unacceptable consequences for the problem owner, in this case the DSO.

2. **Identify loss scenarios (challenges)**

The second step of the analysis is identifying the loss scenarios. These are scenarios that describe the causes of unsafe control actions and hazards. The purpose of identifying loss scenarios is to explain how shortcomings in the design process, insufficient requirements, false feedback and other factors of the implementation and operation of the Digital Twin could result in unsafe control and finally lead to losses (Leveson & Thomas, 2018).

Another purpose of identifying loss scenarios is to show how safe control actions, might be given but not (correctly) carried out. In chapter 3 and 4, the challenges related to the implementation and operation of a Digital Twin were identified, which will be describes as loss scenarios. This step comes second (instead of last) in this research, because in this study the identification of loss scenarios (challenges) is carried out first, and from here the safety control structure are modelled.
The difference between a loss scenario and a system-level hazard is that system-level hazards are higher level hazards in the system than the loss scenarios. In this way, it becomes more apparent which challenges (loss scenarios) affect the system at higher levels.

**3. Identify unsafe control actions**

The third step is to analyse the unsafe control actions caused by the loss scenarios identified in the first step. Functional constraints and requirements around the implementation and operation of the Digital Twin can later be established through identifying the unsafe control actions.

**4. Define controller constraints**

To improve the system safety of the grid and to prevent the hazards that have been identified, controller constraints are identified. Controller constraints describe the actions or system conditions that must be met to avoid unsafe control actions and to eventually prevent losses.

**5. Model the safety control structure**

Finally, the controller constraints identified in step 4, are modelled within a safety control structure. By representing the system as a collection of control loops, a control structure can represent functional links and interactions, crucial to maintain the system safety of the Digital Twin as well as the grid and the people surrounding it.

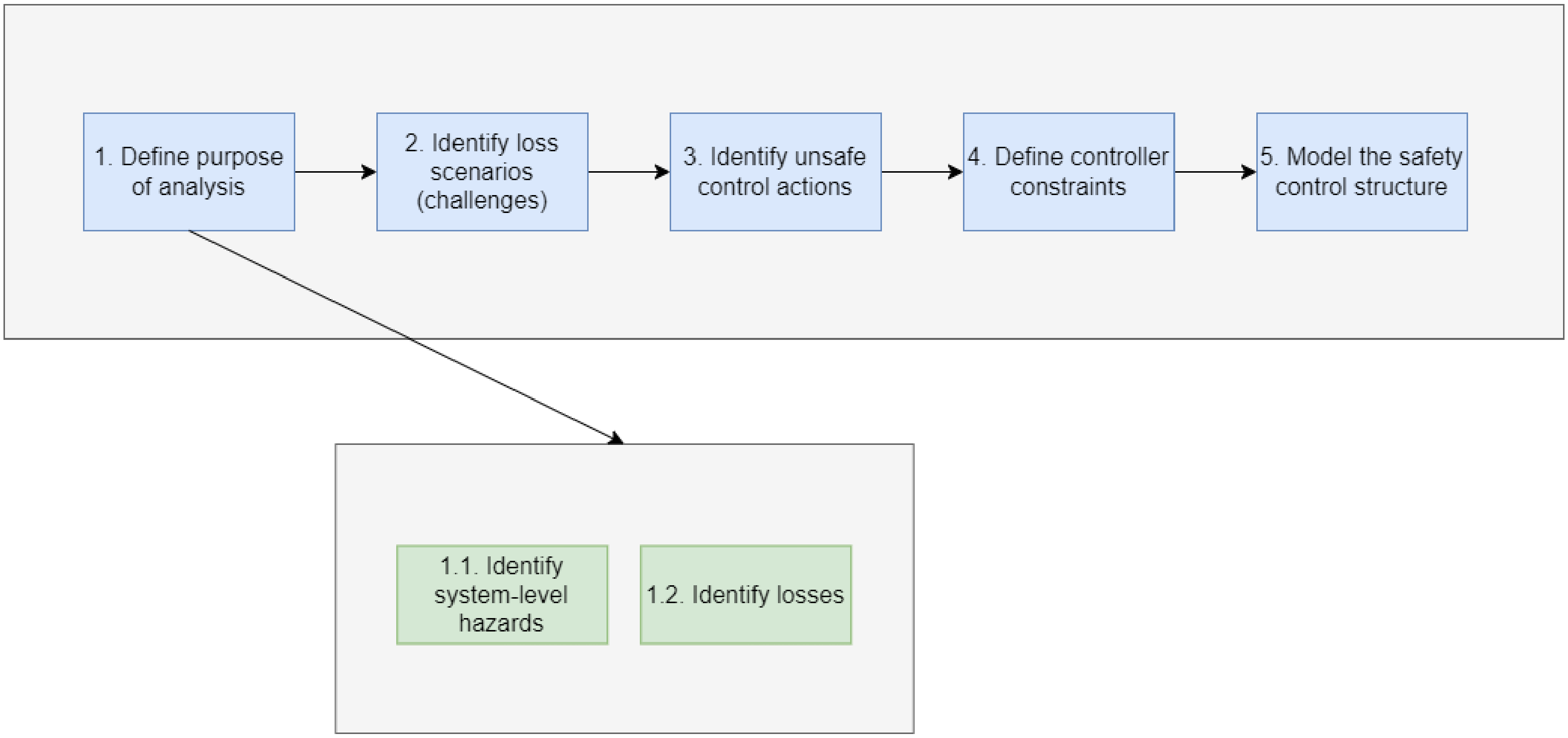


*Figure 3: STPA-inspired analysis structure used in this research*

# 3 Literature research

## 3.1 Introduction to literature research

This chapter will first start with defining the concept of Digital Twins and system safety. Within the literature research, the system safety features for the implementation and operation of different Digital Twin applications for power grids are mapped to answer the first sub-question:
*Which system safety factors have been considered for different applications of Digital Twins in electricity distribution, from a socio-technical perspective?*

Although it has already been noted in the past literature review that few socio-technical features have been identified in the literature, it is still important to map and analyse them in-depth. This will help to get a holistic overview and to provide a foundation for the interviews and the final framework. This is done to gain insight into potential features that are important for the safe implementation of Digital Twins in the power distribution sector, as well as to identify any challenges and opportunities.

Section 3.1.1 defines the concept of Digital Twins, which provides a foundation for understanding their function for power distribution grids. In section 3.1.2, the system safety approach is discussed, emphasising the importance of a holistic approach while implementing Digital Twins. Finally, in section 3.2, the findings from literature will be explained, elaborating on the system safety features and challenges of the implementation and operation Digital Twins. Summaries of the literature can be found in *Appendix C: Literature summary*.

### 3.1.1 Digital Twin concept

Dr. Michael Grieves introduced the concept of the "Digital Twin," or virtual, digital product that is equivalent to a physical product, in 2003 at the University of Michigan Executive Course on Product Lifecycle Management (Grieves, 2015). When the concept was first presented, digital representations of real, tangible products were still in their infancy. Furthermore, limited, manually collected, and primarily paper-based data were being gathered about the physical product as it was being produced. The information technology supporting both the creation and maintenance of the virtual product as well as designing and manufacturing of the physical product has grown dramatically in the decade that followed. Data gathering methods have advanced from manual, paper-based techniques to digital, non-destructive methods using a wide range of physical technologies, such as white light scanning, coordinate measuring machines, lasers, vision systems, sensors, and gauges (Grieves, 2015).

There is no clear official definition of a Digital Twin, which causes misunderstandings regarding what a Digital Twin is between different (academic) areas (Barricelli et al., 2019). Practically speaking, a Digital Twin is defined as follows: it is a virtual representation of a real-life process, object or system, designed to gather data from the actual events to simulate and control current or potential behaviour of the physical twin (Botín-Sanabria et al., 2022). A Digital Twin will mainly rely on data. By using Digital Twins, users and stakeholders can gain an in-depth understanding of any system's internal operations, the interactions between its various components, and the (potential) behaviour of its real-world counterpart. One distinguishing feature of Digital Twins from other digital models is the constant two-way information flow that connects the virtual and physical systems (Metcalfe et al., 2023). Using this communication, a virtual representation mimics the lifecycle of a physical asset or process, allowing decisions to be made that govern the real-world process. Here, automated feedback is not essential; instead, decision-makers can merely incorporate the Digital Twin’s data into their process.

### 3.1.2 System safety approach

Within this thesis, "system safety" refers to the safe implementation and operation of Digital Twins in power grids. System safety, in this context, refers to making sure that no dangerous conditions or failures arise from any (direct or indirect) interactions between the Digital Twin and the physical power grid that could cause harm to the DSO itself, the grid, its operators, and its users. This includes ensuring that the integration of Digital Twins does not compromise the stability, reliability, or security of the power distribution network.

During this research, the safety of the implementation of Digital Twins for DSOs is approached from technical, institutional and process perspective. According to Leveson (2012), safety is an emergent feature of systems which can only be assessed in context with the system as a whole. This means that safety cannot be understood by examining individual grid and Digital Twin components. Instead, (un)safety emerges from the complex interactions between all parts of the grid and the Digital Twin, which emphasises the importance of a holistic and system-wide approach.

Moreover, accidents in complex systems are usually caused by interactions between system components that are all meeting their own requirements (Leveson, 2012). Implementing complex Digital Twins for a critical system like the electricity grid, therefore asks for thorough investigation of different components of the grid, as well as components of the Digital Twin, the environment of a DSO and their digital and physical interactions. It is important to consider not only the reliability or performance of individual components, but also how different components interact and influence each other.

## 3.2 Findings from literature

Analysing and comparing thirteen articles describing different Digital Twin applications within the electricity distribution sector, has led to the identification of several system safety factors. The five most frequent mentioned factors which have been selected are the model performance, input dependence on unreasonable data and data volume, real-world conditions, and model complexity trade-offs. This section will elaborate on these different system safety factors and explain the perspectives of the authors of the different articles.

### 3.2.1 Model performance

A prerequisite for using specific algorithms or methods for a Digital Twin, is model performance. This is the factor that was most frequently highlighted in the articles and described, researched, and tested for most applications. The results of the experiments from Wang et al. (2023), for example, show that the model has a high stability and accuracy and suggest that the research model has a functional value in power grid transformer prediction and life span assessment. In their paper, Yin et al. (2024) show the high accuracy and ultra-real-time processing through electromagnetic transient modelling and parallel computing. They also demonstrate robust fault identification methods that preserve accuracy despite noise and data loss. Other authors that also address and test the model's performance in their paper are Gao and He (2021), who determine the performance from experimental and theoretical perspectives. Additionally, Li et al. (2023) also explain and evaluate the Digital Twin model based on key metrics. Regarding the safety of the Digital Twin, Söderäng et al. (2022) exclusively focus on the accuracy of the models used. Furthermore, Bulatov et al. (2022) highlight the successful creation of a neuro-fuzzy model for a Digital Twin in a DG plant, showing high precision and low variance from experimental data. Moutis and Alizadeh-Mousavi (2021) also mention and demonstrate high calculation accuracy, which successfully captures harmonic content and system errors. Higher sampling rates of the input low voltage waveforms improve the accuracy of the Digital Twin and match the performance of traditional instrument transformers.

### 3.2.2 Input dependence

#### *3.2.2.1 Unreasonable data*

The articles also show how the performance of a Digital Twin is also largely dependent on the information coming in. Yin et al. (2024), for example demonstrate robust fault identification methods that preserve accuracy despite noise and data loss. Nasiri and Kavousi-Fard (2023) also consider that it is essential to be aware of the uncertain inputs for the system's real-time analysis. To simulate the inputs, including the load demands across the grid, Nasiri and Kavousi-Fard (2023) suggest a coefficient model that was derived from the unscented transformation (UT)-based uncertainty model. Furthermore, they applied the suggested uncertainty model to the inputs. Zhan et al. (2020) also handle unreasonable data, by mentioning the preliminary checks which are conducted to optimise unreasonable data before using the power engine to construct the 3D grid.

To improve workforce operations, the paper of Fernandes et al. (2022) explains how the Digital Twin provides real-time monitoring and control capabilities and integrates with virtual reality (VR) and augmented reality (AR). However, the outcome of the Digital Twin depends on smartphone photos made by a field inspector, to be examined in 3D by another inspector (Fernandes et al., 2022). However, if the photo is misrepresented, it could put another inspector at risk.

#### *3.2.2.2 Data volume*

The authors Li et al. (2023) conclude that the key metrics used to evaluate the performance of the model, all increase when the used dataset increases. A reliance on significant data inputs could be hazardous when there is poor data quality or when there is less data available. Moutis and Alizadeh-Mousavi (2021) also explain how higher sampling rates of the input low voltage waveforms improve the accuracy of the Digital Twin and match the performance of traditional instrument transformers.

### 3.2.3 Real-world conditions

A number of articles also mention the importance of considering exogenous factors. Moutis and Alizadeh-Mousavi (2021) explain the importance methods such as field deployment on a distribution system monitoring device to evaluate its performance in real-world conditions, including considerations of installation costs and operational disruptions. Even though the technique is ready to be applied to monitor medium-voltage transformers, this application is still theoretical and would require extensive testing to verify its feasibility in improving grid monitoring. Zie et al. (2019) also suggest that to be able to use the Digital Twin in real-life, the model needs the integration of exogenous factors. Wang et al. (2023) mention that only a fraction of the load conditions is taken into account when examining variations in transformer load rate. When transformers are actually in use, different complex situations arise. Due to the model's limitation in accounting for a limited portion of the load conditions, it may be possible to predict transformer health and remaining life incorrectly, which could result in premature failures or unanticipated downtime, endangering the safety of the system.

### 3.2.4 Model complexity trade-offs

Thus, as previously explained, factors such as data volume can enhance the performance of a Digital Twin model, but on the other hand, these factors can also have negative implications. The authors Li et al. (2023) concluded that the key metrics used to evaluate the performance of the model, all increase when the used dataset increases. However, the clustering algorithms' running times and memory demands also increase with the volume of data (Li et al., 2023). In particular, during crucial operations or peak loads, this can result in processing delays and possible system overload, which might compromise the Digital Twin's reliability. On the other hand, Zhan et al. (2020) explain the Level of Detail Model Technology (LOD), which is a rendering technology to simplify the complexity of 3D models by adjusting the level of detail according to the size and distance to the model from the viewer. Zhan et al. (2020) show that the method leads to a 17% increase in the rendering efficiency of the distribution grid results. However, the limitations or risks of using this simplification method in real-life are not pointed out.

Furthermore, according to Xie et al. (2019), it needs to be studied how model depth will influence prediction errors. Model depth indicates the complexity of the model, including the number of variables and interactions modelled. These analyses will make it possible to control physical assets that belong to various energy vectors within the Digital Twin (Xie et al., 2019). Finally, Bulatov et al. (2022) also mention limitations in model complexity and flexibility that currently exist and emphasise the need for additional research and improvement of the Digital Twin.

### 3.2.5 Implementation of quality standards

Implementing a Digital Twin also requires adhering to certain standards to ensure safe operations. Fernandes et al. (2022) indicate that their Digital Twin is applicable and relevant in the electrical sector to a certain measure. The authors draw attention to the need for high-quality equipment and the complex process of image processing required to produce a functional Digital Twin. In fact, these aspects are critical because they affect the Digital

Twin's accuracy and reliability, which also affects the decision-making and operational safety of the power distribution network. There will have to be quality standards to ensure the reliability of the Digital Twin.

Leopold et al. (2023) explain the benefits of using interoperable geographical Digital Twins as platforms to support the transition to renewable energy resources. The Digital Twin uses open-source technologies, standards, and APIs to integrate data and simulation tools. However, the authors do not go into detail about specific safety protocols or challenges in data security and reliability within these open and interoperable systems. They also do not address the consequences of potential modelling errors or the necessity to regulate the difference between simulated predictions and real-world outcomes.

## 3.3 Conclusion

Thoroughly researching thirteen different articles on applications of Digital Twins in the power distribution sector led to several insights. First, the articles mainly highlight how applying this particular Digital Twin can improve the reliability and efficiency of managing the grid. Besides that, the articles considered a number of socio-technical safety factors for Digital Twins.

The technical system safety aspects that have been addressed in multiple articles are the model performance, input dependence on unreasonable data and data volume, and the consideration of real-world conditions in the Digital Twin model. Analysing the performance of a method or tool of a Digital Twin, is a minimum requirement to consider this method for a Digital Twin application in a critical infrastructure like the power distribution network. Evident from the literature review, this model performance depends significantly on the quality and quantity of the input data. To provide outcomes that do not compromise the safety of the grid and the people around it, it is also important here to consider real-world conditions, which have not been explored in all applications. Besides these technical factors, some institutional factors were also addressed, mainly focusing on the implementation of (quality) standards. These standards are important to ensure a minimal performance of the Digital Twin to mitigate the risk of presenting incorrect or misleading data. Process-related aspects, taking into account the implementation of the relevant Digital Twin application within a DSO, are not mentioned in the articles. In the articles, there was a lack of analysis to the process-related aspects, which describe the implementation of the relevant Digital Twin application within a DSO.

The influence of the concerned Digital Twin applications on the power distribution grid, including any potential implications or system hazards, was generally not significantly discussed in the publications. In fact, publications focus mainly on factors that directly affect the (technical) performance of the algorithms and methods used. This phenomenon is also discussed in recent work of Dobbe (2022), describing how research on AI systems prioritises analysing the computational formulation, the objective of the model and the model's input data and variables. However, single (technical) components should not be separately analysed to evaluate the safety of the entire grid and the people around it, since safety is an emergent property (Leveson, 2012). As a result, it is important to analyse the challenges and opportunities surrounding the implementation of a Digital Twin within a DSO. In addition to the technical aspects of the Digital Twin, this approach also examines how the Digital Twin interacts with other systems, the power grid, the people around it, and other stakeholders.

# 4 Desk Research and interviews

## 4.1 Introduction to desk research and interviews

After identifying the considered system safety factors in literature, regarding the implementation of Digital Twins, desk research will be conducted in this chapter. To get a holistic view of the safety regarding implementation and operation of a Digital Twin within a Dutch DSO, the desk research and interviews will be approached from technical, institutional and process perspective. This desk research will provide a general overview of current systems, processes, regulations, organisational structures and involved processes and stakeholders within a Dutch DSO. The desk research will serve as a foundation for the interviews and ultimately the framework. After the desk research, the most important technical, institutional, and process-related challenges and opportunities that emerged from the interviews will be discussed, finally answering the second sub-question:
*What are the related socio-technical opportunities and challenges associated with the implementation and operation of Digital Twins for Distribution System Operators in the Netherlands?*

## 4.2 Desk research

### 4.2.1 Process conceptualisation

First, the various stakeholders involved and their relationship to the DSO will be discussed. After this, zooming in on the DSO, different processes within the DSO will be mapped out along with their involvement relative to the Digital Twin.

#### *4.2.1.1 Stakeholder analysis*

In order to identify which actors influence the system safety of the power grid, when it comes to the implementation of a Digital Twin, a stakeholder analysis is conducted. The role, interests and relationship to DSOs, with regards to designing, building, using and operating Digital Twins, of each actor involved is shown in Table 3. The overall need is to implement and operate Digital Twins to improve the functioning of the power distribution grid, while ensuring system safety and reliability. The corresponding problem owners are the DSOs.

*Table 3: Roles, interests and interdependencies of stakeholders*

| Actor | Roles | Interests | Relationship with DSO |
|---|---|---|---|
| **Distribution System Operators (DSO)** | Responsible for the design and operation of the Digital Twin. | Interest in system safety and functioning of the distribution grid and the people around it, efficient monitoring and control of the grid, and cost efficiency. | - |

| | | | |
|---|---|---|---|
| **Transmission System Operator (TSO) TenneT** | Responsible for operating the transmission grid, connecting electricity producers to the grid, transporting electricity and matching electricity supply to demand (TenneT, 2023). | Interest in stability and safety of the electricity grid. | Collaborates with TSO for capacity management and balancing the power grid. |
| **Government** | Responsible for establishing regulations and policies for the energy infrastructure, and confidential and personal data. | Interest in reliability of the electricity grid, safe operation of the grid, public safety, sustainability, and innovation. | DSOs and other actors should adhere to government laws and regulations, regarding the implementation and operation of the Digital Twin. |
| **Government regulatory agencies (ACM, AP)** | Enforcement of laws and regulations and supervision of the energy market (Autoriteit Persoonsgegevens, n.d; ACM, 2024). | Preserving privacy of personal data, and a fair and equitable energy market. | DSOs and other actors are monitored for compliance on laws and regulations by ACM and AP. |
| **International Electrotechnical Commission (IEC)** | Provide international standards for electrotechnology (IEC, n.d.). | Ensuring efficiency, safety, interoperability and reliability of electro technologies (IEC, n.d.-a). | DSOs adhere to the international standard for data communication in, and modelling of, electrical substations. |
| **Research institutions** | Conduct research and develop new technologies and methodologies for Digital Twins. | Interest in innovation and knowledge development. | DSOs work with research institutions for innovations and knowledge on technologies. |
| **IT firms** | Development and provision of IT solutions for Digital Twins. | Interest in software innovation, cost efficiency, sales growth and customer satisfaction. | DSOs work together with IT firms for the design and implementation of innovative Digital Twin solutions. |
| **Consultancy firms** | Provide advice and support for the implementation and | Interest in project execution, client relationships, cost efficiency, and knowledge and innovation. | DSOs work together with consultancy firms for the implementation and |

| | | | |
|---|---|---|---|
| | optimisation of Digital Twins. | | optimisation of Digital Twin projects. |
| **Consumers** | Determine electricity demand. | Interest in reliability of the electricity grid and confidentiality of personal data. | DSOs supply electricity to consumers. |

### *4.2.1.2 Processes within DSOs*

The relevant processes have been mapped in this section to provide a perspective on how different processes within a DSO are involved in the development and operation of a Digital Twin. Table 4 lists the various roles and objectives of the processes. Given that the processes of various DSOs may differ, these are common processes that may be referred to differently in practise.

*Table 4: Process responsibilities*

| Department/team | Role | Involvement Digital Twins |
|---|---|---|
| **Company Management** | The leadership and strategic decision-making department of the DSO. Company Management is responsible for the overall direction of the company, policies within the company and long-term planning. | Company Management determines the strategies, priorities and funding for Digital Twin projects. They are also responsible for ensuring that the Digital Twin aligns with the goals of the company. After implementation, Company Management will be responsible for the high-level performance metrics from implementing a Digital Twin. |
| **Safety and Compliance** | Responsible that the DSO adheres to safety regulations and industry standards. | Safety and Compliance departments will ensure that the process of developing a Digital Twin, as well as the operation will adhere to safety regulations and industry standards. |
| **Project Management** | A Project Management team is responsible for managing the design, implementation and operation of solutions within the DSO. | The Project Management team is responsible for managing the design, implementation and operation of the Digital Twin. |
| **Product Development** | A Project Development team is responsible for developing solutions within the DSO, according to the preconditions and standards that have been established. | A Project Development team develops the Digital Twin within a DSO, according to the preconditions and standards that have been established. |

| | | |
|---|---|---|
| **Information Technology (IT)** | IT is responsible for integrating and managing IT systems, data storage and security monitoring, for different departments within a DSO. | IT manages systems and data collections to be integrated within the Digital Twin. |
| **Asset Management** | Manages and optimises the lifecycle of physical assets. | Asset Management can use Digital Twins to monitor assets and predict maintenance. They also maintain asset management systems that can be integrated into a Digital Twin. |
| **Corporate Control** | Corporate Control is responsible for the strategic direction and planning of the DSO. | Corporate Control is responsible for the corporate process systems such as the Geographical Information System (GIS) and the Customer Integration System (CIS). |
| **Distribution Control Centre** | The Distribution Control Centre monitors and controls the distribution grid from a single location, the control centre, or several dispersed control centres using delegated control. (Northcote-Green & Wilson, 2017) | The Distribution Control Centre receives real-time data from the distribution network, which can be incorporated in the Digital Twin. |
| **Operation Technology (OT)** | OT is responsible for managing and maintaining the technology and systems that control and monitor the grid real-time. | OT is responsible for managing and maintaining the technology and systems that control and monitor the grid real-time. |
| **Field Operations** | Field Operations are responsible for maintaining and operating the physical electricity grid, by receiving instructions. | Field Operations are responsible for maintaining and operating the physical electricity grid, by receiving instructions from the Digital Twin. They are also responsible for providing textual or visual input data for the Digital Twin. |

### 4.2.2 Institutional conceptualisation

To get a perspective of how system safety of the power grid is preserved, an overview of current laws, regulations and agreements among various stakeholders is required. To identify key laws, regulations and agreements between different stakeholders that affect the implementation and use of Digital Twins, a formal chart was created. According to Enserink et al. (2022), a formal chart can be created to align the institutions, which is required for effective problem-solving and implementation. The formal chart in Figure 4 shows how one actor must comply with a law, agreement or rule of another actor. It should be noted that every arrow in this formal chart actually represents a resource of dependency. The meaning of the formal rules and their relevance with respect to the implementation and operationalisation of Digital Twins within DSOs, is described below.

**NIS2 Directive**: The Network and Information Security directive (NIS2 Directive), was adopted by the European Union (EU) and aims to improve the cybersecurity and resilience of essential services, such as the power grid, in EU member states (Digitale Overheid, 2024). It also sets strict security standards and incident reporting requirements. The NIS2 Directive therefore ensures security measures of a Digital Twin within a DSO and requires them to manage risks and report incidents.

**Electricity Act 1998**: The Electricity Act 1998 contains rules related to the production, transmission and supply of electricity in the Netherlands (Overheid, 2024). While using Digital Twins, DSOs must comply with regulations on electricity distribution. This act will potentially be replaced by the new Energy Act, focusing on the protection of energy consumers, power grid flexibility opportunities, and the secure exchange of data between grid operators, energy suppliers and customers (Ministerie van Economische Zaken en Klimaat, 2024).

**AI Act**: The purpose of the AI Act is to promote the development and implementation of safe and reliable AI systems in the internal market of the EU (Endendijk, 2024). In addition, the goal is to encourage innovation in the field of AI in Europe while protecting the fundamental rights of EU citizens. AI-powered Digital Twin within DSOs must comply with these ethical standards and safety requirements.

**Data Act**: The Data Act emphasises equitable access and user rights while guaranteeing the privacy of personal data. It is a comprehensive approach to address the issues and unlock the opportunities afforded by data in the European Union (Ministerie van Economische Zaken en Klimaat, 2024b).

**GDPR**: The General Data Protection Regulation (GDPR) is a European regulation that standardises the rules for the processing of personal data by private companies and public authorities throughout the EU (Europese Commissie, 2021). The aim is not only to ensure the protection of personal data within the EU, but also to ensure the free flow of data within the European internal market. The regulation applies worldwide to all companies and organisations that hold and process personal data of natural persons in the EU, including DSOs, the TSO, software providers, research institutions and consultancy firms. With regard to the implementation and operation of Digital Twins, DSOs and other parties concerned must ensure that Digital Twins comply with the GDPR. This involves securing personal data processed by Digital Twins.

**Code of Conduct smart meters:** The rules and regulations for using measurement data from smart meters are outlined in the Code of Conduct for suppliers of smart meters (Energie Nederland, 2021). To make sure that the use of smart metering data complies with legal requirements for processing this (personal) data, energy suppliers can refer to this code of conduct as a guide. The code of conduct guarantees that users of smart meters can take advantage of its benefits without risking their privacy. Digital Twins using smart meter data must comply with the Code of Conduct of smart meters.

**Connection and transport agreement**: The connection and transport agreement between a connected party and a system operator describes the terms and conditions for the connection and transport of electricity (TenneT, 2019). DSOs must therefore make sure that the functioning of the Digital Twin aligns with the terms and conditions of the connection and transport agreements.

**Operational protocols**: Operational protocols are guidelines and procedures for the operation of electricity distribution grids. Digital Twins must be developed and operated complying with operational protocols.

**Cooperation agreement**: The cooperation agreement is in this case an agreement between TenneT and Dutch DSOs, which outlines the terms of collaboration and shared responsibilities regarding the electricity grid in the Netherlands. Digital Twins must be developed and operated in accordance with cooperation agreements.

**Non-Disclosure Agreement (NDA)**: An NDA is a binding contract, which enables DSOs to share confidential information with external parties (Netherlands Chamber of Commerce, 2024). The other party agrees to withholding and not disclosing certain information. NDAs are used when external parties collaborate in developing and maintaining a Digital Twin and are given access to sensitive information to do so.

**NTA 8120**: NTA 8120 provides requirements for an asset-related safety, quality and capacity management system of electricity networks (Stichting Koninklijk Nederlands Normalisatie Instituut, n.d.). DSOs and external parties using Digital Twins for asset management need to make sure that the Digital Twin complies with NTA 8120 requirements.

**Communication norms and protocols**: The DSOs will establish communication protocols to be used for (mutual) data exchange (Overheid, 2019). This communication protocol will also determine which important communication, such as a shutdown instruction, will be registered. Software for implementing Digital Twins, provided by software providers, must comply with these communication norms and protocols.

**Technology standards**: Technology standards from the International Electrotechnical Commission (IEC) are international standards for electrical components and equipment (IEC, n.d.-a). These technology standards make sure that DSOs and software providers develop Digital Twins in compliance with industry standards.

**NWO Grants**: The government facilitates personalised funding for individual researchers to promote research with scientific and societal impact (NWO, 2024). Researchers conducting research on Digital Twins for DSOs can apply for NWO funding.

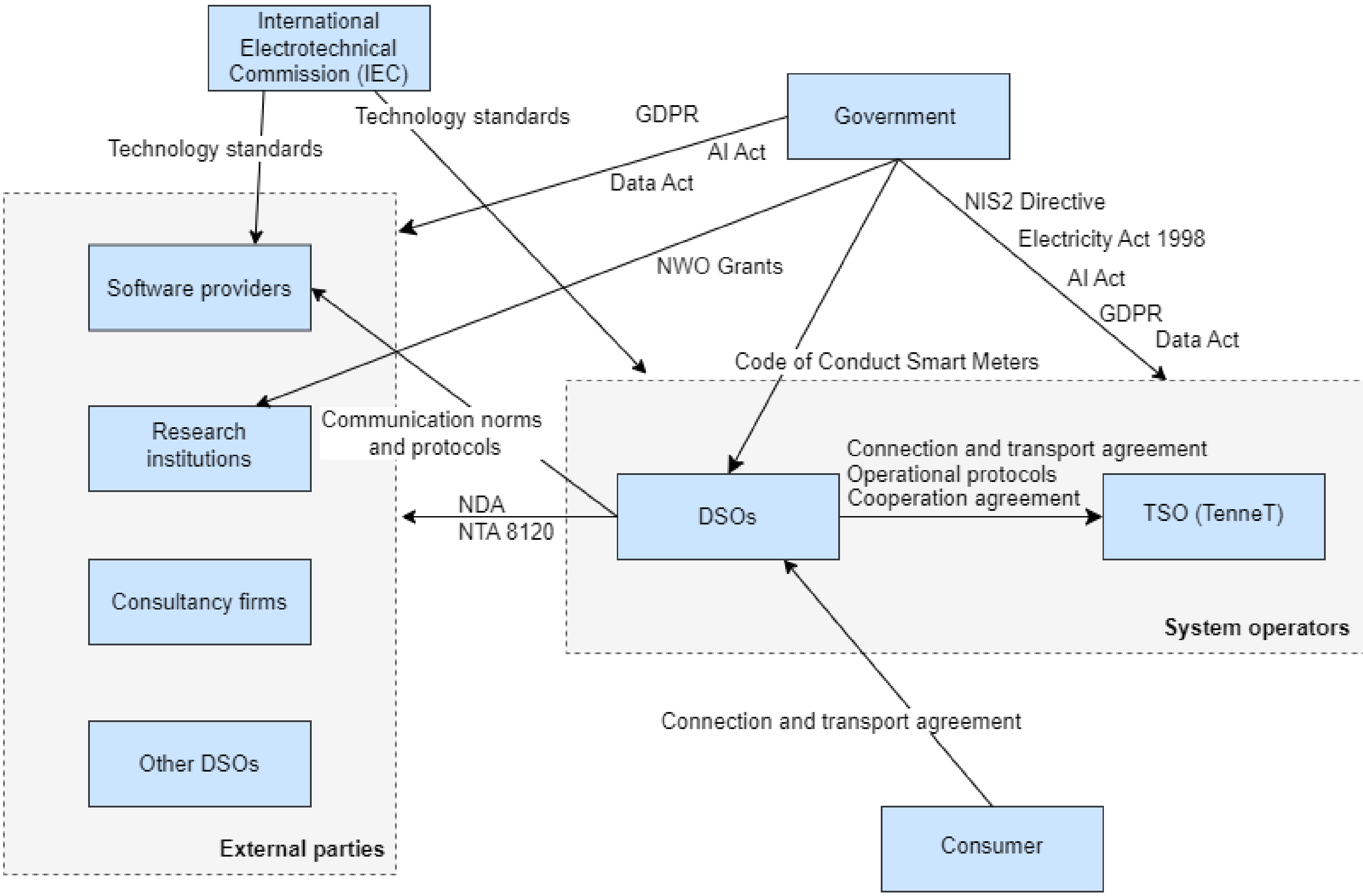


*Figure 4: Formal chart (Enserink et al., 2022)*

### 4.2.3 Technical conceptualisation

To better understand the interactions between different processes within a DSO and the different systems that need to be integrated with each other, the disparate systems needed to implement a Digital Twin are identified in this section. This section also discusses the functionality and features of the systems and how these systems communicate with each other. This electricity system within DSOs is analysed using the power utility control hierarchy of Northcote-Green and Wilson (2017), which identifies various systems and dependencies relevant to the system safety of the grid. This information was supplemented and confirmed with information obtained from the interviews. Finally, this section shows a framework in Figure 5, established to illustrate how systems and processes control each other.

As explained in Section 4.2.1.2., the grid is being controlled from the **Distribution Control Centre (DCC)**, or several distributed control centres using delegated control. The DCC is responsible for a process called **Supervisory Control And Data Acquisition (SCADA)**, which depends on connectivity between the DCC and the **primary asset** (i.e. circuit breaker, generator, tap changer, etc.) that is supposed to be operated (Northcote-Green and Wilson, 2017). State estimation in SCADA uses algorithms to analyse real-time sensor data and predict the internal states of parts of the grid, used for monitoring and control.

**Actuators** or other mechanisms to carry out specific operations must be installed in primary devices. An **Intelligent Electronic Device (IED)** is a **secondary asset** that needs to be interfaced with these actuators. The IED interconnects the actuator with the data transmission system. High-speed sensors called **Phasor Measuring Units (PMUs)** monitor the power system's voltage and current. Direct **consumer**-system interaction represents the lowest level of control. In order to facilitate easy tariff revision and load control, more adaptable metering systems are becoming essential. **Automatic Meter Reading (AMR)** systems are being implemented along with IT-based accounting and billing procedures to achieve this functionality.

The **Advanced Distribution Management Systems (ADMS)** is part of the DCC and gives the operator the best "as operated" view of the grid. Using the non-real-time data from IT, required to appropriately control and maintain the grid on a regular basis, the ADMS coordinates all downstream real-time operations. In order to provide operators with a workspace that enables intuitive execution of tasks, an adequate human-machine interface and process-optimised command structures are key. **The Distribution Automation System (DAS)** is a sub-system of the ADMS and covers all the real-time features of the control process. As can be seen in the diagram, this system consists of the local automation and remote-controlled assets at substations, along with the communication network. In any power distribution network, the majority of the distribution assets are not remotely controlled. As the operations of DSOs depend on effective control of these assets, extra functionalities provided to the DMS are required, namely specific applications from **Corporate Control** systems like the **Geographic Information System (GIS)** and the **Customer Information System (CIS)**.

**Asset Management** manages the **Enterprise Asset Management System (EAMS)**, used to manage the physical assets through their lifecycle. They use real-time asset data from the OT department, and non-real-time historical asset data from the IT department.

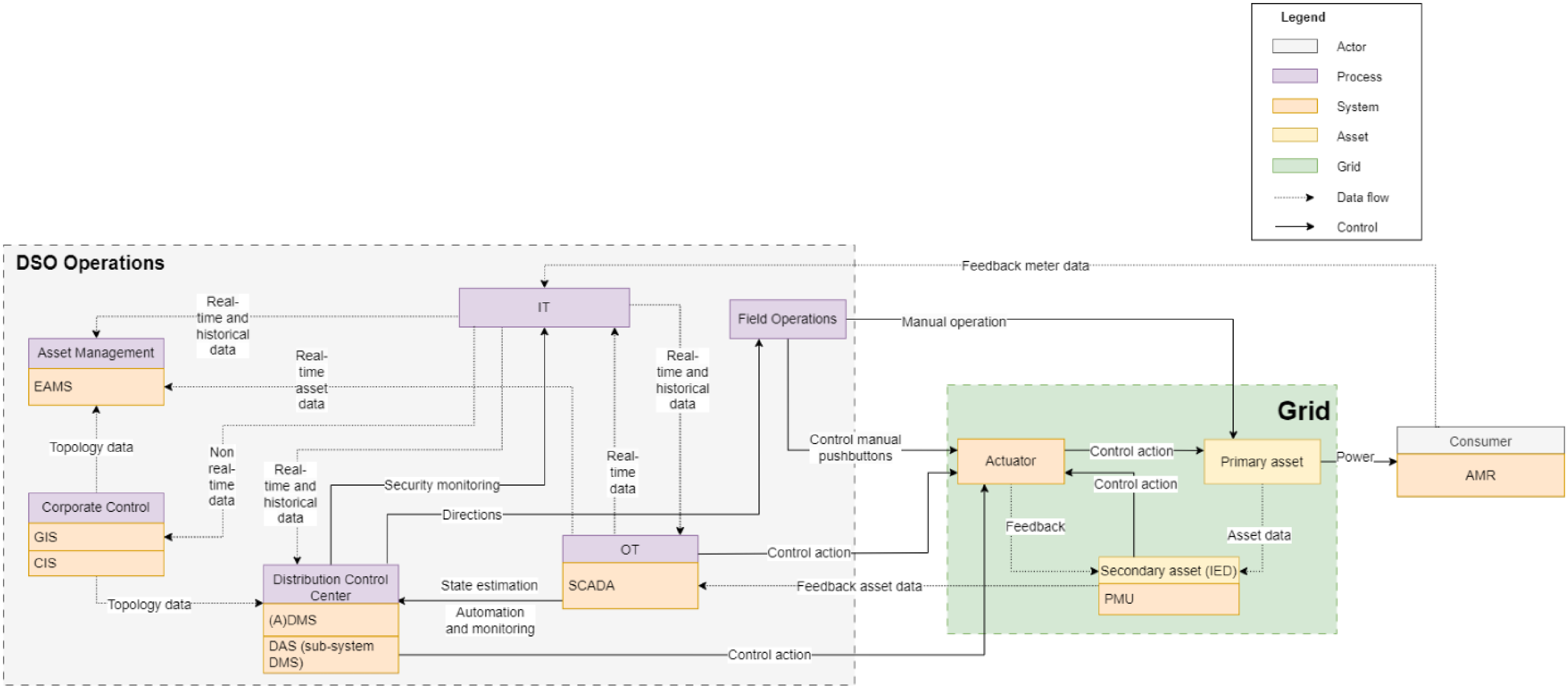


*Figure 5: Current technical framework of systems and flows within DSO*

## 4.3 Interview results

In this section, the results of the interviews are discussed, focusing on the technical, institutional, and process-related challenges and opportunities associated with the implementation and operation of Digital Twins within DSOs.

The technical, institutional and process conceptualisations presented earlier in this chapter mapped out the key systems, processes, actors and regulatory environments relevant to a Digital Twin. The interviews were designed to build upon this conceptualisation by gathering real-world insights and experiences from professionals directly involved in the field. By finally linking the conceptualisation to the interviews, the research provides a comprehensive understanding of how Digital Twins can be implemented in power grids, combining theoretical rigor with practical relevance.

To find out how specific socio-technical opportunities and challenges related to the implementation and operation of Digital Twins for DSOs in the Netherlands affect system safety, the opportunities and challenges are identified through the interviews. To get a complete overview of this, the focus will be on technical, institutional and process characteristics of Digital Twin implementation and operation.

This section incorporates the results of nine interviews. The challenges and opportunities that emerged most clearly have been detailed in the results. Other results can be found in *Appendix D: Summaries of interviews*, as well as further details about the backgrounds of the interviewees.

### 4.3.1 Technical challenges and opportunities

The technical aspects that emerged from the interviews will be discussed in this section. The aspects that will be elaborated upon are system integration, data quality and integrity and data integration.

#### *4.3.1.1 System integration*

A key element of developing a Digital Twin at a DSO is the integration of existing systems. Interviewee 7 emphasises the challenge of achieving a "complete representation of your network," noting the inconsistencies between vendor promises of simplicity and the complex reality of integrating with established IT infrastructures. According to interviewee 7, the Digital Twin is driven by one crucial element, which is the asset data. This data often already exists within a DSO, but the challenge is that this data is captured in various systems. Interviewee 7 mentioned that to see all the current data of an asset, data is needed from the Supervisory Control and Data Acquisition (SCADA) system, as well as from the DMS (Document Management System), Outage Management System (OMS), Advanced Distribution Management System (ADMS) or Energy Management System (EMS). Interviewee 8 explains that the representation of assets in the grid are visible in the Geospatial Information System (GIS). However, to obtain real-time data of the assets, a connection to the SCADA-system, for example, is required. Simulation tools are then needed again to run simulations. Interviewee 7 emphasises that these systems already exist within a DSO, but the data from these various systems must be made available so that it can be accessed at any time.

Interviewee 8 also discusses the integration of Information Technology (IT) and Operational Technology (OT) systems, which is crucial but challenging due to their traditionally separate functions. A difference between IT and OT is that OT systems like SCADA collect real-time, or near real-time data. However, IT systems like the Customer Information System (CIS), may have a delay of several minutes to a day. For every team different use cases have been established, but what is missing to develop a Digital Twin is the interoperability between different systems.

Interviewee 3 also stresses the challenge of IT and OT alignment. The design of several legacy systems has not yet taken into account the possibility of interconnection. This problem, according to interviewee 3, rests partly with the software vendor, but also partly from within the IT side. According to interviewee 3, this problem is a generic problem among DSOs. Similarly, interviewee 4 highlights the difficulty of merging data from various teams into a single, coherent model, underscoring the practical obstacles in achieving effective data integration.

Interviewee 2 also identifies specific application challenges to the computational demands as a significant barrier, especially when integrating existing systems with new Digital Twin technologies. Moreover, when integrating different systems, a lot of computational resources might be needed to run the models. According to interviewee 2, there is room for improvement around these resources, such as algorithms and computational approaches to power systems, which is also an academic question.

#### *4.3.1.2 Data quality and integrity*

Maintaining data quality and integrity is a significant challenge in the development of Digital Twins within DSOs, as stated by experts from the field. According to interviewee 7, it is important to first look at what asset data is available and what data is actually relevant, which starts with the sensors in the network. Interviewee 7 emphasises the importance of data governance and master data management strategies to maintain the integrity of data throughout its lifecycle. An essential requirement is clear asset linkage of data from sensors, like temperature and vibration monitors, for data to be valuable. Another important feature according to interviewee 7 is the taxonomy around the assets, since the asset categorisation can be improved within DSOs. In addition, output data must be standardised to be used within a logical data model. This is challenging considering how data is managed differently across different departments within DSOs, pointing out the variations in practices even within the same company.

Interviewee 4 expands on this by explaining the operational need to connect topological data with real-time measurements to accurately determine network states. According to interviewee 4, the lack of measurement data is a challenge in developing Digital Twins. To improve data quality, as mentioned by interviewee 4 and interviewee 6, more sensors should be installed to take more measurements. However, interviewee 6 also mentions the labour-intensive and costly process of expanding sensor networks to achieve the required data granularity. In addition, regulations impede the use of specific data. For example, there are restrictions on the use of smart meter data due to data protection regulations.

Interviewees 9, 6 and 3 emphasise the critical role of ongoing data validation and management. Interviewee 9 notes the importance of data checks to ensure data is not only accurate but also secure from potential cyber threats, suggesting a comprehensive data management strategy as essential for reliable operations.

Moreover, interviewee 3 mentions that innovative approaches are needed to continuously improve data quality, such as using machine learning to detect patterns or anomalies that may indicate data inaccuracies. Interviewee 3 explains that data management is an evolving process that requires both technological innovation and practical fieldwork, the latter to obtain information from the grid.

#### *4.3.1.3 Data integration*

Data integration is crucial for system integration in the context of Digital Twins for DSOs, because it ensures that multiple separate data sources within the organisation are harmonised and accessible in a unified format. However, the integration of different data sources into a Digital Twin, is considered as a challenge according to the experts in the field.

Interviewee 7 stresses the need for shifting away from conventional data management techniques and towards a more integrated strategy. He highlights the need to repurpose data, which was originally relevant to asset management alone, to support advanced applications like condition-based and predictive maintenance across multiple functional features. In order to achieve this, a comprehensive integration strategy is needed, mirroring the basic idea of data lakes but with an emphasis on continuous data feeding to enable real-time operational insights. This will ensure that data extracted from various platforms is efficiently de-siloed and made easily accessible. However, interviewee 2 outlines how large computing resources are required for modelling Digital Twins real-time, particularly when aiming for a single source of truth that can offer an overall view of different operational variables.

Moreover, concerns surrounding the technical capacities required to manage disparate data types and sources while implementing Digital Twins, are expressed by interviewee 5. According to interviewee 5, standardizing data handling is still a significant challenge within DSOs. Additionally, interviewee 5 explains how difficult it is to merge data from several domains, like the grid, the telemetry, the forecasting domain, into a single information model. The technical challenge, according to interviewee 5, is “because a DSO who is traditionally not set up for that, to actually put all those layers of information into a model or into an ontology that is actually usable”. Furthermore, interviewee 3 discusses the broader impact of these integration challenges in the context of the digitalisation layer of system operations. In order to understand how systems could evolve from more specific solutions to standardised services, interviewee 3 suggests looking at models like Worldly maps.

#### *4.3.1.4 Technical complexity*

The interviews show that it is important to think carefully about the technical complexity of a Digital Twin. On the one hand, an accurate representation of reality involves a detailed model. However, there is a risk involved if the model gets overly complicated and too complex for everyone involved to understand.

When it comes to the complexity of the Digital Twin, interviewee 7 explains the dynamic character of the Digital Twin and how these systems need to be constantly updated and integrated across various platforms within the company's architecture, as they develop. This complexity increases when the Digital Twin supports several use cases and provides real-time data synchronisation, which is essential when changes on the grid must be instantly reflected in the twin to preserve accuracy and safety of the system. Moreover, interviewee 2 notes the significant resources needed to run exhaustive models that cover the range of DSO operations, underlining the computational issue. In order to reduce risks, interviewee 2 recommends a "human in the loop" strategy that makes sure human monitoring enhances the skills of the Digital Twin, especially when it comes to interpreting model outputs.

Concerning the interpretability of a complex Digital Twin, interviewee 9 emphasises the need for clear visualisations in Digital Twins for DSOs. In order to keep the system from turning into an incomprehensible "black box," effective visualisation makes sure that operators in control rooms are able to quickly understand and act upon the data and recommendations offered. In power networks, such transparency is critical for making well-informed decisions and running day-to-day operations reliably. Adding to this, interviewee 5 also mentions organisational and systemic integration challenges. According to interviewee 5, in order to prevent ambiguities in data interpretation and system responses, it is imperative that different teams or departments have a shared understanding of the information model.

Interviewee 1 brings up an important argument on the intrinsic drawbacks of using Digital Twins as reality models. He states that the only phenomena a Digital Twin can replicate are those that are specifically programmed into it. Due to this constraint, the inclusion of elements and degradation phenomena in the model must be carefully considered, as any oversight may result in differences between the Digital Twin's predictions and the actual behaviour of the system, which could cause a safety issue. Interviewee 1 goes into further detail on the implications of the complexity and the processing demands of modelling large network interactions. He adds that models must be intentionally simplified in order to avoid computational overload and still capture important effects on network behaviour. This fine line must be managed in order to preserve the Digital Twin as a valuable tool without creating a false sense of safety from incorrect or inadequate modelling.

Expanding on this, interviewee 3 explains how strategic use of Digital Twins also involves optimising network measurement to enhance the safety of the grid. While it might be possible to measure the entire network, the value derived from such an extensive data collection might not be optimal. Through repeated updates based on actual measurements, Digital Twins enable targeted measurements at critical positions, improving the accuracy of the model. By creating models that accurately capture the most important elements of network operations, this approach to sensor deployment and data collection increases the system's observability and also improves its safety.

### 4.3.2 Institutional challenges and opportunities

The institutional aspects that arose from the interviews and will be discussed in this section are regulatory issues. This includes problems that the interviewees have encountered or expect to encounter while implementing or using the Digital Twin, along with suggestions on how to deploy regulations.

#### *4.3.2.1 Regulatory issues*

The implementation and operation of Digital Twins also requires regulatory changes besides the physical infrastructure. As highlighted by interviewee 7, clear agreements need to be made about the digital delivery of a system, for example concerning the interoperability or standardisation (like the IEC61850 protocol). This standardisation ensures that Digital Twins can communicate effectively across different platforms within the network. Before finalising agreements about the digital delivery, it has to be determined what the Digital Twin needs exactly which is often challenging to clarify according to interviewee 7.

The shift towards data-driven decision-making within DSOs, requires a constant monitoring of the data, in interviewee 7’s view. This requires a greater focus on data governance, ensuring that the stored data is compliant. interviewee 7 also suggests the establishment of certain principles, such as a system of record that contains all asset information.

Interviewee 9 and interviewee 1 appoint the need for clear contractual agreements and responsibilities, especially as Digital Twin projects involve multiple stakeholders like software providers and engineers. Agreements must be established to ensure that all parties understand their responsibilities. This includes arrangements about how to proceed if issues arise with the Digital Twin after the implementation project is completed. Additionally, it is important to define who will be responsible for further development, ongoing maintenance, and reliability of the Digital Twin, as well as who will ensure it continues to function. To protect privacy-sensitive data, interviewee 1 suggests the possibility to use dummy data instead of real-time data when collaborating with other parties in the implementation phase.

Another regulatory challenge, according to interviewee 8, is integrating the contractual agreements in a Digital Twin. Interviewee 8 mentions that there is currently no virtual representation of contract within the Digital Twin. The integration of these contracts is essential to indicate and apply constraints, so that anyone doing any planning or operating on the grid, knows the repercussions of the grid itself as well as the resulting finances. A convergence play between the contractual team and the engineering team is required to implement these contracts in a Digital Twin, which does not exist right now.

Interviewee 2 suggests adopting more decentralised control structures. The importance of data storage will also increase, emphasising decisions about what data should be stored or discarded, distinguishing between actual data and errors, and considering what is necessary for future model predictions. According to interviewee 2, this process needs more refinement than currently exists. This also calls for better alignment between IT and OT structures, which is challenging because they are usually segregated.

On the other hand, interviewee 4 and interviewee 6 mention that data quality can be enhanced by using more measurement data like smart meter data. To be able to use these data, it needs to be substantiated to the government that privacy can be safeguarded. Furthermore, interviewee 1 and interviewee 4 stress the fine balance between leveraging detailed operational data and ensuring its confidentiality.

### 4.3.3 Process challenges and opportunities

The process-related aspects that emerged from the interviews will be discussed in this section. The aspects that will be elaborated upon are the development approach of the Digital Twin, collaborations within DSOs and stakeholder collaboration.

#### *4.3.3.1 Development approach*

Since Digital Twins are generally complex systems, it is important to take a structured approach to the development of these types of systems. Despite the fact that this appears apparent, experts claim that it is frequently slightly more complicated in practice and that many important steps in the development process are overlooked. As suggested by interviewees 1, 7, and 8, determining which phenomenon would be interesting to be investigated is a crucial first step of the development process in avoiding overly complex models. Interviewee 1 explains that before determining which variables serve as input, the requirements of the Digital Twin must be considered. These requirements need to be fully understood in order to establish clear boundaries for the Digital Twin and to have a complete understanding regarding the output of the model as well as the excluded factors. For instance, interviewee 1 provides the following example of determining the required size of the data's time steps: "Am I speaking of an electrical study? Subsequently, you can compute an entire year or potentially multiple years using hourly time steps. Is it about very fast phenomena, namely electricity switching phenomena, then you make a whole different simulation”.

Furthermore, use case-driven methodology is stressed by both interviewee 7 and interviewee 8 when developing Digital Twins. As interviewee 1 also points out, interviewee 7 thinks it is fundamental to first enumerate every prerequisite in this regard. This method involves identifying specific applications for Digital Twins, such as asset performance management and predictive maintenance. The strategy of first delineating the scope of the model and setting boundary constraints, guarantees that decision-makers will ultimately have a clear understanding of the precise output of the model.

#### *4.3.3.2 Collaborations within DSOs*

Given that different applications of Digital Twins include the need to incorporate different existing data models used in different teams within a DSO, close collaboration is inevitable to ensure the quality of a Digital Twin. Several interviewees indicated that collaboration between different teams within a DSO for system and data integration can be challenging. Interviewee 8 explains that what is missing is a so-called “digital thread”, an end-to-end information flow of a product and the process across all departments within a DSO. Every team has their own use cases. According to interviewee 8, a digital thread is essential for obtaining interoperability between various digital systems inside a DSO, such as IT (Information Technology) systems, OT (Operational Technology) systems, and GIS (Geospatial Information Systems). Not only interviewee 8, but also interviewees 5, 3 and 2 emphasise the challenge and relevance of close collaboration between IT and OT departments. The issues encountered in managing real-time data across DSO domains were brought to light by interviewee 5. To improve the responsiveness and flexibility of grid management, the importance of incorporating data from the IT domain into the OT domain, was emphasised by interviewee 5.

Interviewee 2 acknowledges that a unified approach to data management is necessary, pointing out that as Digital Twins become more complex, interdisciplinary collaboration becomes increasingly important. System architects and electrical engineers, for example, need to collaborate closely to make sure that Digital Twins appropriately represent the state of the network and are capable of detecting and solving errors. Accurate and up-to-date network models depend on systems like GIS, integrating with EMS and DMS, according to interviewee 3. It is not only challenging to technically integrate these systems, as mentioned before, but also to coordinate and manage the collaboration between different departments involved.

Additionally, interviewee 7 noted that departments frequently do not communicate data among one another, instead using only the information necessary to come to a certain decision. In order to create a Digital Twin that incorporates information from for example the ADMS, GIS, and EAMS, the control room and asset management will need to collaborate closely. Interviewee 7 claims that there are cultural and historical reasons for this challenging collaboration for data integration. According to interviewee 6, it can be challenging to collaborate with different departments because of different mindsets. Interviewee 6 mentions that “there are departments that have a more progressive mindset and there are departments that have a more conservative mindset, and the biggest challenge is to coordinate them together”.

#### *4.3.3.3 Stakeholder collaboration*

Results from the interviews show that it is important but challenging to collaborate with other parties to develop and maintain Digital Twins. Not only within DSOs, but also among different DSOs in the Netherlands, standardisation of data models is needed according to interviewee 7. This standardisation is required to facilitate data integration and interoperability across systems. Interviewee 2 also mentions the necessity of shared standards and protocols to guarantee that different systems can communicate with one another without risking systems safety or data integrity. The same perspective is shared by interviewee 4, who recommends increased cooperation between DSOs to exchange problems and solutions encountered regarding the implementation of Digital Twins, which could lead to more effective problem solving and resource utilisation.

Interviewee 1 goes into more detail on the intensive, although limited, partnerships with tech firms to model particular parts of the Digital Twin, such as wind turbines. These partnerships are necessary to incorporate real-time modifications to the digital representation of the network, which has an immediate effect on system safety. The need to "speak the same language", in terms of software and model interpretation raises challenges in achieving smooth integration and operational consistency.

Interviewee 8 and interviewee 4 both talk about the dependency on external technology companies for software development capabilities. Interviewee 8 observes a trend where DSOs are creating their own software in order to become less dependent on other vendors. However, he acknowledges that the collaboration with software providers remains indispensable due to their expertise in bridging gaps between traditional DSO operations and cutting-edge software demands. According to interviewee 8, this raises the concern that much of the technical expertise required to implement and manage Digital Twins is often housed within technology companies. This dependency creates a gap in technical capabilities within DSOs, making external partnerships not only beneficial but also necessary. The challenge of outsourcing technical deployments, however, is that on the one hand, the tech company must have sufficient knowledge of the power grid to successfully implement a model. On the other hand, the DSOs must also have sufficient knowledge of the operation of the Digital Twin to properly interpret the output and detect any errors.

## 4.4 Conclusion

The interviews identified various socio-technical related challenges and opportunities associated with the implementation and operation of Digital Twins for DSOs in the Netherlands. The second research question is: *What are the socio-technical related opportunities and challenges associated with the application of Digital Twins for distribution system operators in the Netherlands?*

The most important technical factors that emerged from the research were system integration, data quality and integrity, data integration, and technical complexity. The interviewees also identified several regulatory challenges to consider. Factors that emerged regarding the design, implementation and maintenance process of the Digital Twin were the development approach, collaboration within DSOs and collaboration with other stakeholders. Figure 6 shows that many technical and process-related statements were made during the interviews, relative to institutional. One reason may be that many regulations are taken as given and people are used to taking them into account. With regard to technical and process-related factors, it mainly emerges that current technologies and processes need to change in order for a Digital Twin to implement and operate. As a result, the interviewees encountered several obstacles that have been identified in these interviews.

Within a critical system such as the power grid, safety measures must already be considered during the design of a new technical product such as a Digital Twin. The identified challenges emphasise the importance of focusing on system safety constraints. For example, a lack of clear data governance may compromise data quality and integrity, leading to the use of incorrect labelled data as input for the Digital Twin. By focusing on system safety during the design and operational processes of the Digital Twin, the addressed challenges can be regulated or controlled. The next chapter will elaborate on the safety constraints based on the identified challenges. In addition, the interactions of the challenges will be summarised in a framework.

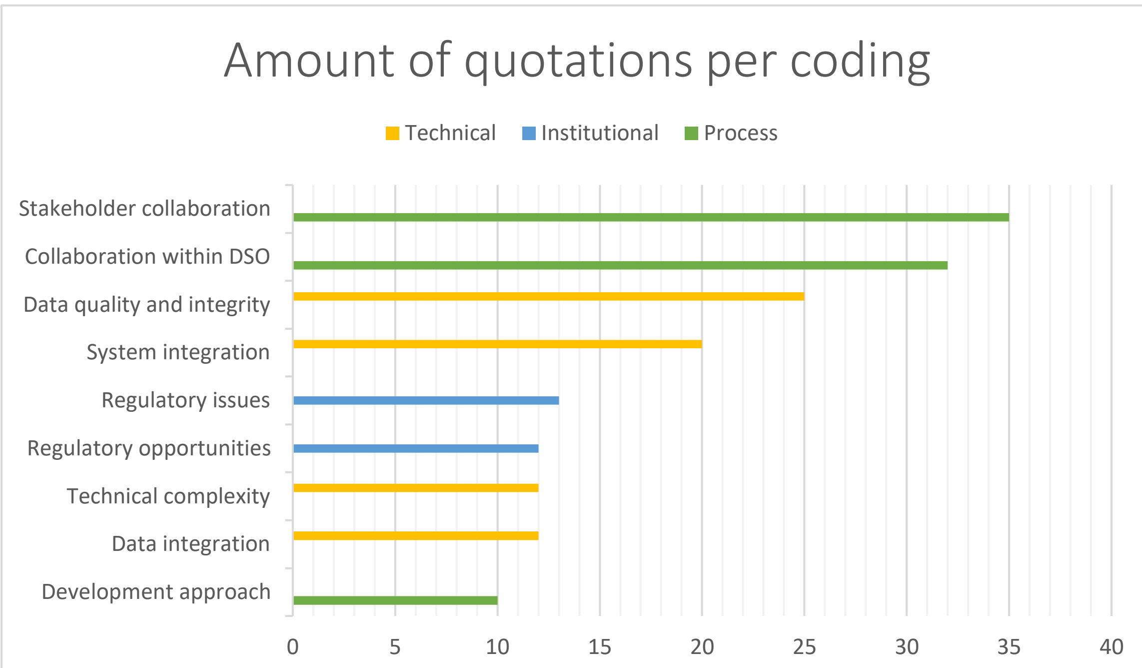


*Figure 6: Amount of quotations per coding*

# 5 Safety control structure

## 5.1 Introduction to STPA-analysis

The method used to develop the safety control structure is based on the System-Theoretic Process Analysis (STPA) from Leveson and Thomas (2018) and is thoroughly explained in the methodology in section 2.4.1. The socio-technical factors identified in the previous chapters are structured into a framework in this chapter. The framework is in the shape of the safety control structure, presented by Leveson (2012). The safety control structure is a suitable framework to structure the findings from the previous chapters, since it considers socio-technical safety factors related to a technology (sub-)system. According to Leveson (2012), the safety control structure is used to manage safety, which is considered as an emergent property resulting from interactions between system components. The socio-technical factors identified in previous chapters are analysed on how they affect the safety of the power grid, answering the third research question in section 5.7: *How do the identified factors associated with the implementation and operation of Digital Twins affect the system safety of the grid?*

The identified socio-technical factors are used to eventually generate safety constraints that guide the implementation and operation of Digital Twins within a DSO, considering system safety. The constraints are incorporated in the safety control structure to see how these affect the whole electricity grid, and the processes, systems, people and stakeholders involved and how they interact with each other. This finally provides an answer (in the conclusion) to the main research question: *What are the key system safety factors for a Distribution System Operator to consider for the implementation and operation of a Digital Twin?*

The STPA-inspired analysis in this research, will first define the purpose of the analysis (section 5.2) then identify the loss scenarios (section 5.3), unsafe control actions (section 5.4) and controller constraints (section 5.5), and finally model the safety control structure (section 5.6). Figure 7 shows the structure of this analysis. Nevertheless, it is important to mention that the STPA analysis is an iterative process. The different parts of the STPA-inspired analysis are therefore not strictly performed in this order, but it can be used as a guideline to perform a similar analysis. The traceability that is maintained between the outputs of the various steps of the analysis, can be found in Figure 2. At the end of this chapter, the most important constraints are selected and further analysed.

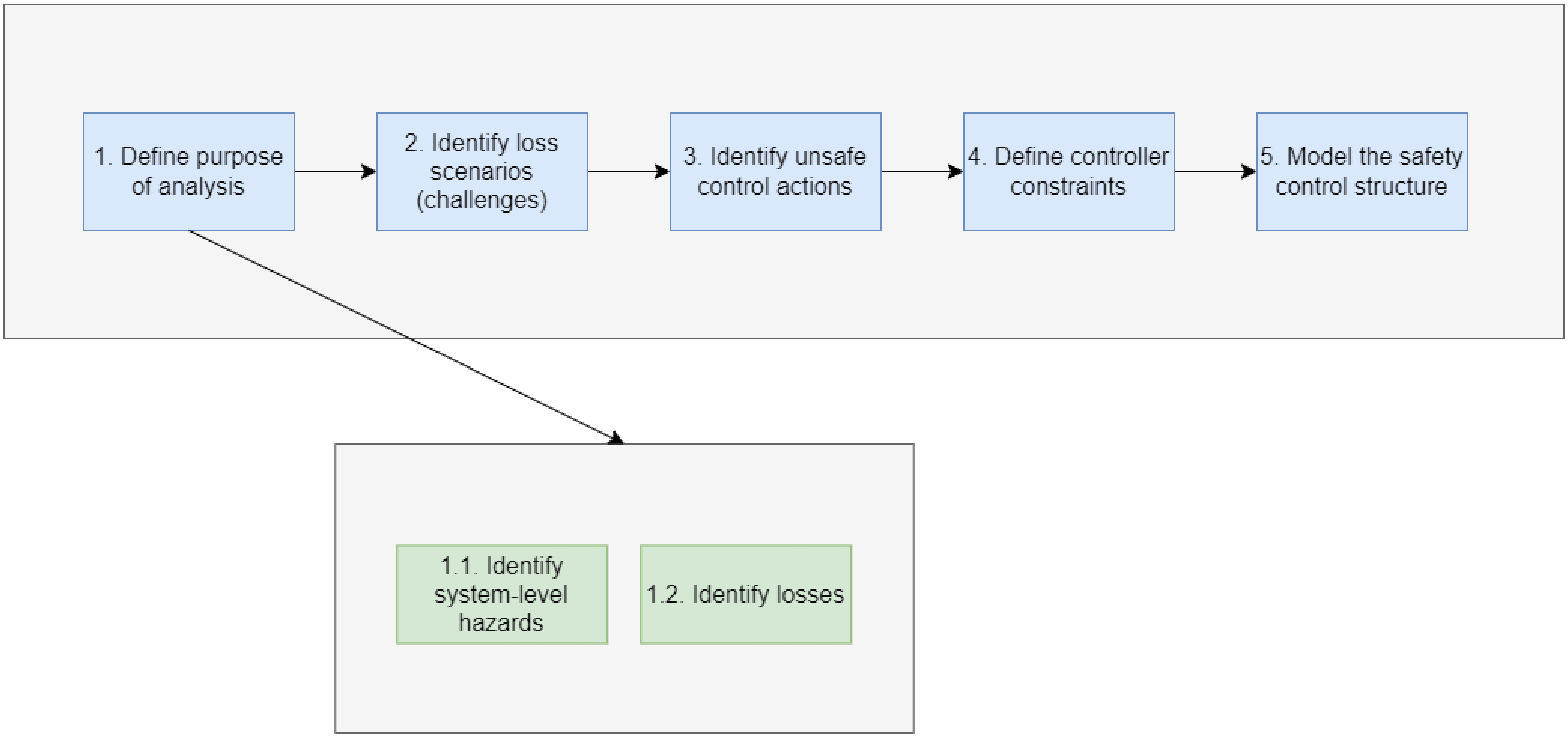


*Figure 7: STPA-inspired analysis structure used in this research*

## 5.2 Purpose of framework

The first step of the analysis is to define the purpose of the analysis, so what losses regarding the safety of the implementation and operation of Digital Twins the analysis will strive to prevent. This will consist of two steps, namely to identify system-level hazards and to identify losses.

### 5.2.1 Identification of system-level hazards (H)

Determining the hazards associated with the implementation and operation of Digital Twins is the next step. A hazard is a condition of a system, or a collection of circumstances that, when combined with a specific set of the worst possible environmental circumstances, will result in a loss (Leveson and Thomas, 2018). The final losses will be identified in the next paragraph. The system in this case is the combination of all technical, institutional and process-related factors identified in previous chapters, that influence the implementation and operation of Digital Twins for DSOs directly or indirectly. The identified system-level hazards are shown in Table 5.

*Table 5: System-level hazards*

| System-level hazard |
| --- |
| H-1: Unauthorised access to sensitive data by external third parties |
| H-2: Digital Twin not complying to identified industry protocols, safety laws and regulations |
| H-3: Inaccurate Digital Twin models |
| H-4: Ambiguous Digital Twin representations |
| H-5: Overly complex Digital Twin models |
| H-6: Digital Twin failure caused by lack of computational power |

### 5.2.2 Identification of losses

This paragraph will identify the potential losses of the system, when implementing and operating Digital Twins within a DSO. Leveson and Thomas (2018) specify that a loss includes something that has value for stakeholders, and losing it is considered to be unacceptable. The losses are a result of the system-level hazards. Since the DSOs are the problem owner of the problem approached in this study, the losses that are unacceptable to the DSOs are identified in Table 6.

*Table 6: Losses*

| Losses |
| --- |
| L-1: Loss of life or injury to field workers |
| L-2: Damage to electrical infrastructure |
| L-3: Loss of sensitive information |
| L-4: Financial loss |
| L-5: Loss of electrical power network reliability |
| L-6: Loss of reputation |

### 5.2.3 Purpose

Now that the specific losses, system-level hazards and system-level constraints have been identified, it is clear which risks this analysis aims to prevent. The main losses which the safety control structure in the next section will aim to prevent are the loss of life or injury to field workers, damage to electrical infrastructure, loss of sensitive information, financial loss, loss of electrical power network reliability and loss of reputation. The next sections will explain how specific scenarios can lead to system-level hazards and losses.

## 5.3 Identification of loss scenarios (LS)

In this paragraph the loss scenarios will be identified. These are scenarios that describe the causes of unsafe control actions and hazards. The aim of identifying loss scenarios is to explain how shortcomings in the design process, insufficient requirements, false feedback and other factors of the implementation and operation of the Digital Twin could result in unsafe control and finally lead to losses. In chapter 3 and 4, the challenges related to the implementation and operation of a Digital Twin were identified. This section will put the challenges from chapters 3 and 4 into the format of loss scenarios. This is done by writing down the challenges in the form of an occurring scenario (i.e. the challenge that the data quality of the input data is often poor within a DSO, is outlined in Loss Scenario 1: Input data quality is poor). The sections in which the corresponding challenges have been explained are referenced.

The identified system-level hazards that are potentially caused by the loss scenarios are shown in Table 7. *Appendix F: Losses that result from loss scenarios and hazards* shows how the loss scenarios lead to system-level hazards and finally to the corresponding losses.

### 5.3.1 Technical loss scenarios

**Input data**

LS-1: Input data quality of Digital Twin is poor (3.2.2.1 & 4.3.1.2)

LS-2: There is a lack of measurements (4.3.1.2)

LS-3: There is insufficient data for acceptable model performance of Digital Twin (3.2.2.2 & 4.3.1.2)

LS-4: There is a lack of data standards for Digital Twin input data (4.3.1.3 & 3.2.5)

**Systems**

LS-5: The systems integrated in the Digital Twin are not easily interoperable (4.3.1.1)

**Model complexity**

LS-6: The model only accounts for a limited portion of conditions (3.2.3 & 4.3.1.4)

LS-7: Handling large volumes of data can cause computational overload (3.2.4 & 4.3.1.4)

LS-8: The visualisations of the Digital Twin are unclear (4.3.1.4)

LS-9: More input variables are used than necessary (4.3.1.4)

LS-10: The accuracy of the Digital Twin’s models or algorithms is considerably low (3.2.1 & 4.3.1.4)

### 5.3.2 Institutional loss scenarios

LS-11: The required safety and communication protocols and regulations of the Digital Twin are not clear to everyone involved in the development process (4.3.2.1)

LS-12: Confidential data is not handled carefully (4.3.2.1)

LS-13: The DSO lacks adequate data governance (4.3.2.1)

### 5.3.3 Process Loss Scenarios

**Development**

LS- 14: The Digital Twin development team does not use a structured development approach (4.3.3.1)

**Collaboration**

LS-15: There is a lack of internal technical expertise (4.3.3.3)

LS-16: Departments are hesitant to collaborate on the implementation and operation of Digital Twins (4.3.3.2)

*Table 7: System-level hazards resulting from loss scenarios*

| Loss scenarios | System-level hazard |
|---|---|
| LS-12 | H-1: Unauthorised access to sensitive data by external third parties |
| LS-11 & 12 | H-2: Digital Twin not complying with identified industry protocols, safety laws and regulations |
| LS-1 – 6, 10, 13 & 16 | H-3: Inaccurate Digital Twin models |
| LS-4, 8 & 16 | H-4: Ambiguous Digital Twin representations |
| LS-9, 14 & 15 | H-5: Overly complex Digital Twin models |
| LS-7 | H-6: Digital Twin failure caused by lack of computational power |

## 5.4 Unsafe control actions (UCAs)

This paragraph identifies the potential unsafe control actions caused by the loss scenarios identified in the previous section. Functional constraints and requirements around the implementation and operation of the Digital Twin can later be established through identifying the unsafe control actions.

### 5.4.1 Technical UCAs

**Input data**

LS-1: Input data quality of Digital Twin is poor

- UCA-1.1: Using the low-quality data in the Digital Twin without validation

LS-2: There is a lack of measurements

- UCA-2.1: Not enough sensors have been installed to capture necessary measurements

LS-3: There is insufficient data for acceptable model performance of Digital Twin

- UCA-3.1: Developing a Digital Twin despite the data insufficiencies

LS-4: There is a lack of data standardisation and/or categorisation for Digital Twin input data

- UCA-4.1: Using unstandardised and uncategorised datasets as input for the Digital Twin

**Systems**

LS-5: The systems integrated in the Digital Twin are not easily interoperable

- UCA-5.1: The integration of systems without ensuring compatibility

**Model complexity**

LS-6: The model only accounts for a limited portion of conditions

- UCA-6.1: Developing a Digital Twin model that ignores occurring conditions

LS-7: Handling large volumes of data can cause computational overload

- UCA-7.1: Feeding large volumes of data into the Digital Twin leading to computational overload

LS-8: The visualisations of the Digital Twin are unclear

- UCA-8.1: Using complex visualisations that are not interpretable by everyone using the Digital Twins

LS-9: More input variables are used than necessary

- UCA-9.1: Including more variables than necessary in the model without enhancing the accuracy of the Digital Twin

LS-10: The accuracy of the Digital Twin's models or algorithms is considerably low

- UCA-10.1: Using Digital Twins without validating and testing the algorithms on accuracy

### 5.4.2 Institutional UCAs

LS-11: The required safety and communication protocols and regulations of the Digital Twin are not clear to everyone involved in the development process

- UCA-11.1: Not providing everyone involved in the development process of the Digital Twin with information on safety and communication protocols and regulations

LS-12: Confidential data is not handled carefully

- UCA-12.1: Allowing unauthorised access to confidential data

LS-13: The DSO lacks adequate data governance

- UCA-13.1: Not establishing clear data governance regulations within the DSO

### 5.4.3 Process UCAs

**Development**

LS-14: The Digital Twin development team does not use a structured development approach

- UCA-14.1: Not having the preconditions of the Digital Twin clearly mapped out
- UCA-14.2: Using redundant variables that do not improve the performance of the Digital Twin
- UCA-14.3: Not having the purpose of the Digital Twin clear before the development of the Digital Twin

**Collaboration**

LS-15: There is a lack of internal technical expertise

- UCA-15.1: Outsourcing development without internal oversight

LS-16: Departments are hesitant to collaborate on the implementation and operation of Digital Twins

- UCA-16.1: Departments/teams work siloed

## 5.5 Defining controller constraints (C)

To enhance the system safety of the grid and to prevent the system-level hazards that have been identified, controller constraints are identified in this paragraph. Controller constraints describe the actions or conditions that must be met to avoid unsafe control actions and eventually prevent system-level hazards and losses (Leveson and Thomas, 2018).

The constraints are shown in Table 8, along with the system-level hazards they attempt to prevent. In this way, it is shown how constraints can improve system safety on system-level. *Appendix G: The constraints that mitigate or prevent loss scenarios* shows which loss scenarios are reduced or prevented by the constraints.

*Table 8: Safety constraints to prevent system hazards*

| System-level constraints | System-level hazards to be prevented |
|---|---|
| C-1.1: Perform data quality validation checks | H-3: Inaccurate Digital Twin models |
| C-2.1: Provide alerts when there is insufficient measurement data | H-3: Inaccurate Digital Twin models |
| C-3.1: Implement strategies to generate sufficient data | H-3: Inaccurate Digital Twin models |
| C-3.2: Automated actions taken by Digital Twins must be validated and monitored by human controller | H-3: Inaccurate Digital Twin models |
| C-4.1: Establish clear data taxonomy and data standards | H-3: Inaccurate Digital Twin models<br>H-4: Ambiguous Digital Twin representations |
| C-4.2: Categorise and standardise data before using it as input for the Digital Twin | H-3: Inaccurate Digital Twin models<br>H-4: Ambiguous Digital Twin representations |
| C-5.1: Provide middleware and translation layers to facilitate system integration | H-3: Inaccurate Digital Twin models |
| C-6.1: Test the Digital Twin model on different conditions | H-3: Inaccurate Digital Twin models |

| | |
|---|---|
| C-7.1: Optimise algorithms within Digital Twin to handle large volumes of data | H-6: Digital Twin failure caused by lack of computational power |
| C-7.2: Establish data strategies for occasions of large volumes of input data | H-6: Digital Twin failure caused by lack of computational power |
| C-8.1: Test visualisations on interpretability on all departments and stakeholders working with the Digital Twin | H-4: Ambiguous Digital Twin representations |
| C-9.1: Establish clear performance objectives of the Digital Twin | H-5: Overly complex Digital Twin models |
| C-9.2: Perform sensitivity analysis to choose most important variables | H-5: Overly complex Digital Twin models |
| C-10.1: Set constraints on the minimal accuracy of the models | H-3: Inaccurate Digital Twin models |
| C-10.2: Test models on accuracy | H-3: Inaccurate Digital Twin models |
| C-11.1: Provide everyone involved in the Digital Twin development process with trainings on safety and communication protocols and regulations | H-2: Digital Twin not complying to identified industry protocols, safety laws and regulations |
| C-12.1: Provide everyone involved in the development process and operation of the Digital Twin with trainings on data confidentiality | H-1: Unauthorised access to sensitive data by external third parties |
| C-13.1: Establish clear data governance regulations within the DSO | H-2: Digital Twin not complying to identified industry protocols, safety laws and regulations<br>H-3: Inaccurate Digital Twin models |
| C-13.2: Establish a data governance department within the DSO | H-2: Digital Twin not complying to identified industry protocols, safety laws and regulations<br>H-3: Inaccurate Digital Twin models |
| C-14.1: Document a structured Digital Twin development approach | H-5: Overly complex Digital Twin models |
| C-14.2: Establish regulations and guidelines for teams/departments to adhere to the structured Digital Twin development approach | H-5: Overly complex Digital Twin models |
| C-15.1: Use a digital thread to design, evaluate and manage the Digital Twin collaboratively with IT firms | H-5: Overly complex Digital Twin models |
| C-15.2: Hire Digital Twin experts to gain knowledge in-house | H-5: Overly complex Digital Twin models |

| | |
|---|---|
| C-15.3: Use consultants to bridge the knowledge gap between DSOs and IT firms | H-5: Overly complex Digital Twin models |
| C-16.1: Establish collaborative objectives aimed at system integration between different relevant departments | H-3: Inaccurate Digital Twin models<br>H-4: Ambiguous Digital Twin representations |

## 5.6 Framework: Safety control structure

The last step is to develop a framework of the system, called a safety control structure. The constraints identified in 5.5., will be modelled within a safety control structure. According to Leveson and Thomas (2018), the behaviour of the entire system will be constrained by an effective control structure, which in this case means that the power grid, as well as the Digital Twin, the DSOs and other stakeholders are all constrained. By representing the system as a collection of control loops, a control structure is able to represent functional links and interactions to maintain the system safety of the Digital Twin as well as the grid and the people surrounding it.

### 5.6.1 Aggregated model

Usually starting from an abstract level, the control structure is iteratively developed to capture more information about the system. As the foundation for the safety control structure, components (sections 4.2.1, 4.2.2, and 0) of the technical, institutional and process-related conceptualisation were aggregated into a single model. The aggregated model is visible in Figure 8. This model shows the current control actions of a DSO, relevant for the implementation of Digital Twins. In this way, the model shows how through a hierarchy structure, control of the system is determined.

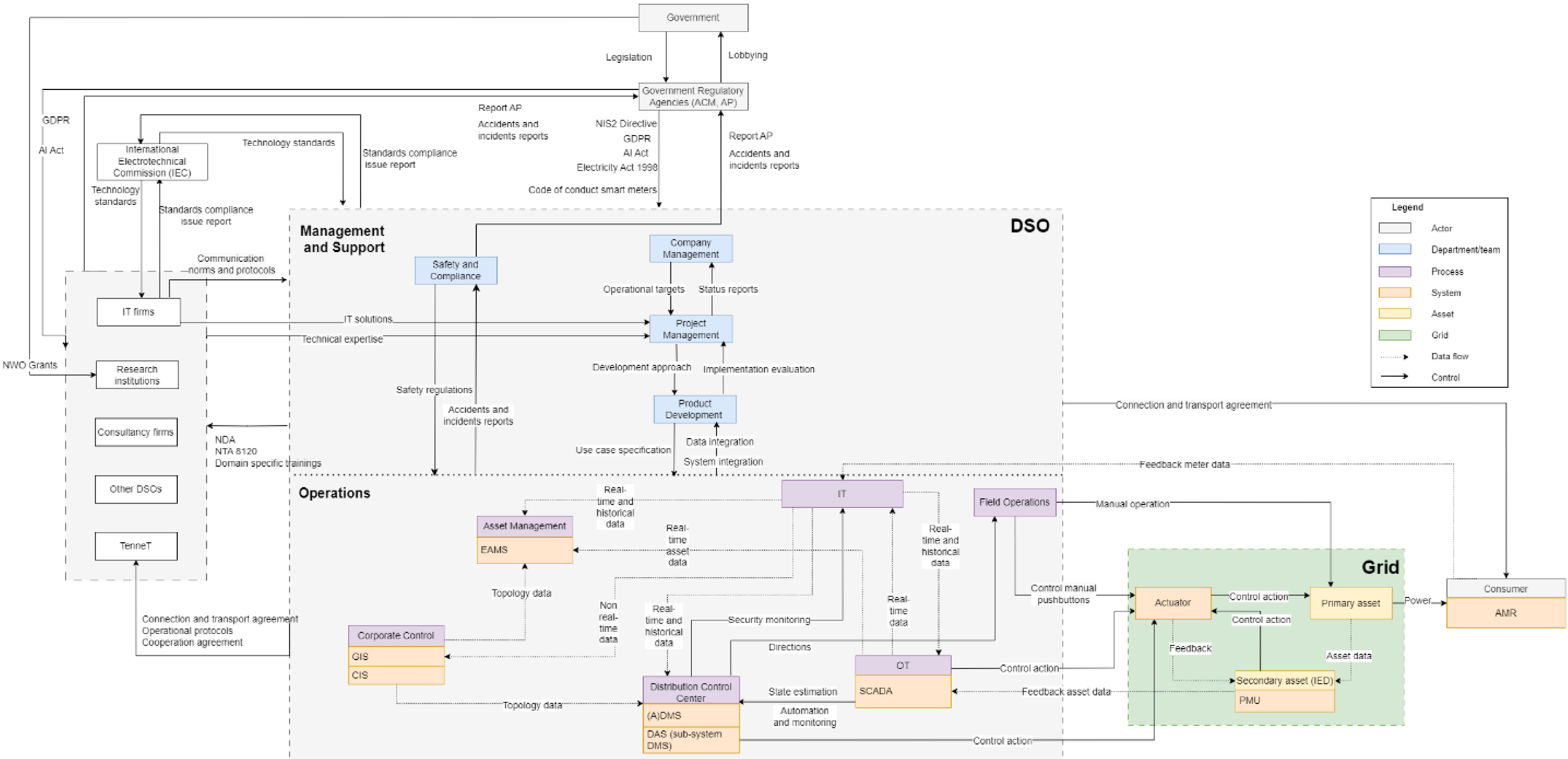


*Figure 8: Aggregated model of technical, institutional and process-components*

### 5.6.2 Safety control structure

In the final safety control structure, shown in Figure 9, the constraints identified in section 5.5. have been added to the model. The Digital Twin system was also added, to show the interactions between different systems, processes, and departments/teams. In this way, each arrow shows a safety constraint that contributes to the system safety of both the grid and the people around it. The constraints can be viewed where they are applicable. Thus, one can immediately see where the constraints affect the system safety of the grid directly and indirectly.

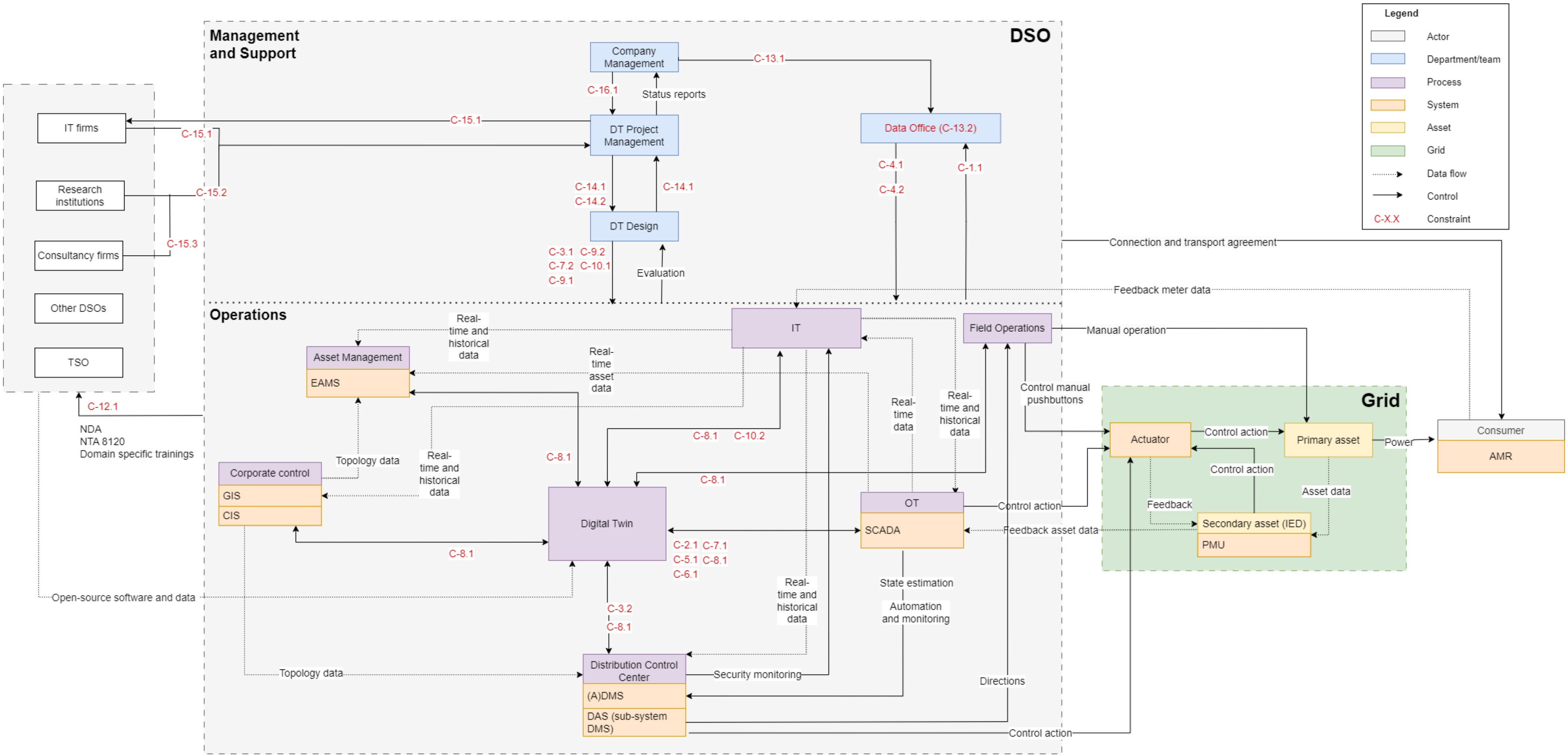


*Figure 9: Safety control structure with safety constraints in red*

## 5.7 Interventions: further analysis of constraints

In this section, several constraints are discussed in more detail. All constraints, established from corresponding loss scenarios, unsafe control actions, system level hazards, are shown in a complete overview in *Appendix H: Complete overview of constraints, loss scenarios, unsafe control actions, system-level hazards and losses*. The constraints are divided into three themes: technical, institutional and process constraints. The technical, institutional and process-related constraints which emerged most evidentially in the interviews and literature are further analysed. This section provides an answer to the third sub-question:

*How do the identified factors associated with the implementation and operation of Digital Twins affect the system safety of the grid?*

### 5.7.1 Recurring themes

Table 9 on the next page shows all constraints categorised within different recurring themes in interviews and literature research. The most recurring themes are the system integration, standardisation and collaboration among teams/departments. These themes were chosen for deeper analysis because they arose from the research as the most significant challenges that need to be addressed for the safe implementation and operation of Digital Twins in the power distribution sector.

*Table 9: Constraints within recurring themes*

| Technical, institutional and process associated constraint | |
|---|---|
| Technical | **Data quality and volume** |
| | • C-1.1: Perform data quality validation checks<br>• C-2.1: Provide alerts when there is insufficient measurement data<br>• C-3.1: Implement strategies to generate sufficient data |
| | **System integration** |
| | • C-5.1: Establish collaborative objectives aimed at system integration between different relevant departments |
| | **Model performance** |
| | • C-10.1: Set constraints on the minimal accuracy of the models<br>• C-10.2: Test models on accuracy<br>• C-9.1: Establish clear performance objectives of the Digital Twin<br>• C-9.2: Perform sensitivity analysis to choose the most important variables |
| | **Computational power** |
| | • C-7.1: Optimise algorithms within Digital Twin to handle large volumes of data<br>• C-7.2: Establish data strategies for occasions of large volumes of input data |
| Institutional | **Standardisation** |
| | • C-4.1: Establish clear data taxonomy and data standards<br>• C-4.2: Categorise and standardise data before using it as input for the Digital Twin |
| | **Compliance protocols and regulations** |
| | • C-11.1: Provide everyone involved in the Digital Twin development process with training on safety and communication protocols and regulations<br>• C-12.1: Provide everyone involved in the development process and operation of the Digital Twin with training on data confidentiality<br>• C-13.1: Establish clear data governance regulations within the DSO<br>• C-13.2: Establish a data governance department within the DSO |
| Process | **Automation** |
| | • C-3.2: Automated actions taken by Digital Twins must be validated and monitored by human controllers |
| | **Real-world Implementation** |
| | • C-6.1: Test the Digital Twin model under different conditions |
| | **Collaboration among teams/departments** |
| | • C-14.1: Document a structured Digital Twin development approach<br>• C-14.2: Establish regulations and guidelines for teams/departments to adhere to the structured Digital Twin development approach<br>• C-16.1: Establish collaborative objectives aimed at system integration between different relevant departments |
| | **Collaboration with stakeholders** |
| | • C-15.1: Use a digital thread to design, evaluate, and manage the Digital Twin collaboratively with IT firms<br>• C-15.2: Hire Digital Twin experts to gain knowledge in-house<br>• C-15.3: Use consultants to bridge the knowledge gap between DSOs and IT firms<br>• C-16.1: Establish collaboration guidelines |

**System integration** was identified by seven of the nine interviewees as an important technical challenge. The complexity of integrating different existing systems, such as SCADA, GIS, and DMS, with the Digital Twin was consistently mentioned. Interviewees identified several issues, including the difficulties in coordinating IT and OT systems, and the discrepancies between vendor claims of simplicity and the reality of integrating with existing IT infrastructures.

**Standardisation** was identified as an institutional challenge, discussed by six interviewees and cited in the literature. The need for standardised protocols and data handling is important to ensure interoperability and safety while implementing and operating Digital Twins. Without clear and consistent standards, the risk of data inconsistency and ambiguousness of the Digital Twin increases, which could compromise the effectiveness and interpretability of the Digital Twins.

**Collaboration among teams/departments** is noted as a key process-related challenge, mentioned by eight interviewees. The implementation and operation of Digital Twins require collaboration across different teams within the DSOs. Interviewees highlighted the need for a structured development approach and clear communication to overcome organisational silos and ensure that all departments are aligned in their objectives and processes.

### 5.7.2 Analysis of key constraints

In this section, the key technical, institutional and process-related constraints within the most recurring themes (system integration, standardisation, and collaboration among teams/departments) are analysed in detail. Each constraint is discussed in terms of its importance for the safe implementation of Digital Twins, the potential risks if the constraint is not adhered to, and the minimal requirements needed to satisfy each constraint.

#### *5.7.2.1 Technical constraints: system integration*

***1. C-5.1: Provide middleware and translation layers to facilitate system integration***

**Necessity**

The perk of a Digital Twin within a DSO is to combine data from different systems into one representation. However, it is considered challenging to integrate IT systems, such as GIS and asset management, with OT systems, like SCADA and EMS. Therefore, middleware and translation layers are necessary to ensure that data from different systems, which may use different formats or protocols, can be effectively integrated and interpreted within the Digital Twin.

**Potential risks if not adhered to**

Without appropriate middleware and translation layers, data from different systems may not be compatible, leading to integration failures. This could result in incomplete or inaccurate data being fed into the Digital Twin, leading to operational errors. Operational errors in the power grid could cause loss of life or injury to field workers, damage to electrical infrastructure, financial loss, and/or loss of electrical power network reliability. Table 10 shows how the loss scenario can potentially lead to unsafe control actions, system-level hazards and losses.

**Minimal requirements**

- Implement middleware that can handle data translation and integration across all relevant systems.
- Ensure that the middleware is scalable and can adapt to future changes in system architecture or data formats.
- Regularly test and update middleware to maintain compatibility and performance.

**Acknowledging the risk**

Even with middleware and translation layers, it might be impossible to achieve seamless integration due to inconsistent data formats and legacy systems. DSOs should acknowledge possible limitations of the middleware and develop strategies to work with these limitations. This includes acknowledging that certain data might not be integrated or may require manual intervention, and understanding how this limitation impacts the overall operation and decision-making processes.

*Table 10: Constraint C-5.1 preventing unsafe control actions, caused by specific loss scenario, and therefore system-level hazards and losses*

| Constraint | Loss scenario | Unsafe control action | System-level hazard | Loss |
|---|---|---|---|---|
| **C-5.1: Provide middleware and translation layers to facilitate system integration** | **LS-5:** The systems integrated in the Digital Twin are not easily interoperable | **UCA-5.1:** The integration of systems without ensuring compatibility | H-3: Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |

### *5.7.2.2 Institutional constraints: standardisation*

#### *1. C-4.1: Establish clear data taxonomy and data standards*

**Necessity**

Within DSOs, there is a lack of data standardisation and/or categorisation. A clear data taxonomy and standardised data formats are important for ensuring that data can be consistently managed, accessed, and interpreted across the organisation and within a Digital Twin.

**Potential risks if not adhered to**

Without having clear data standards for the input data of the Digital Twin, there is a risk of data inconsistencies, errors, and misinterpretations of the data. This could eventually lead to incorrect decisions being made based on Digital Twin outputs which could cause loss of life or injury to field workers, damage to electrical infrastructure, financial loss and/or loss of electrical power network reliability. Table 11 shows how the loss scenario can potentially lead to unsafe control actions, system-level hazards and losses.

**Minimal requirements**

- Develop a standardised data taxonomy that is used across all departments and systems.
- Regularly update data standards to reflect changes in technology, regulation, and organisational needs.
- Ensure that all data entering the Digital Twin conforms to these standards before being processed.

**Acknowledging the risk**

Within the large and complex organisation structure of DSOs, using legacy systems, achieving data standardisation across all systems and departments may not be feasible. Data might for example also lack labelling, making it impossible to standardise the data. DSOs must acknowledge the limitations in standardising the data and focus on managing the risks involved. This might involve accepting certain data quality issues and adjusting the used variables or purpose of the Digital Twin to that, so that the Digital Twin remains accurate and unambiguous.

*Table 11: Constraint C-4.1 preventing unsafe control actions, caused by specific loss scenario, and therefore system-level hazards and losses*

| Constraint | Loss scenario | Unsafe control action | System-level hazard | Loss |
|---|---|---|---|---|
| **C-4.1: Establish clear data taxonomy and data standards** | **LS-4:** There is a lack of data standardisation and/or categorisation for Digital Twin input data | **UCA-4.1:** Using unstandardised and uncategorised datasets as input for the Digital Twin | **H-3:** Inaccurate Digital Twin models<br>**H-4:** Ambiguous Digital Twin representations | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |

### 2. *C-4.2: Categorise and standardise data before using it as input for the Digital Twin*

**Necessity**

Categorising and standardising data before it enters the Digital Twin ensures that the system operates on accurate, reliable, and compatible data, which is important for accuracy of the Digital Twin.

**Potential risks if not adhered to**

If data is not standardised before being used in the Digital Twin, there is a risk of feeding incompatible or incorrect data into the system, which could lead to faulty outputs and decisions that endanger grid safety. This could eventually lead to incorrect decisions being made based on Digital Twin outputs which could cause loss of life or injury to field workers, damage to electrical infrastructure, financial loss and/or loss of electrical power network reliability. Table 12 shows how the loss scenario can potentially lead to unsafe control actions, system-level hazards and losses.

**Minimal requirements**

- Implement a data preprocessing pipeline that categorises and standardises all data inputs.
- Use automated tools to check for data conformity and flag any discrepancies before the data is used by the Digital Twin.
- Regularly review and refine the data standardisation process to ensure it remains effective.

**Acknowledging the risk**

Within the large and complex organisation structure of DSOs, using legacy systems, achieving data standardisation across all systems and departments may not be feasible. Data might for example also lack labelling, making it impossible to standardise the data. DSOs must acknowledge the limitations in standardising the data and focus on managing the risks involved. This might involve accepting certain data quality issues and adjusting the used variables or purpose of the Digital Twin to that, so that the Digital Twin remains accurate and unambiguous.

*Table 12: Constraint C-4.2 preventing unsafe control actions, caused by specific loss scenario, and therefore system-level hazards and losses*

| Constraint | Loss scenario | Unsafe control action | System-level hazard | Loss |
|---|---|---|---|---|
| **C-4.2: Categorise and standardise data before using it as input for the Digital Twin** | **LS-4:** There is a lack of data standardisation and/or categorisation for Digital Twin input data | **UCA-4.1:** Using unstandardised and uncategorised datasets as input for the Digital Twin | **H-3:** Inaccurate Digital Twin models<br>**H-4:** Ambiguous Digital Twin representations | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |

#### 5.7.2.3 Process constraints: collaboration among teams/departments

***1. C-14.1: Document a structured Digital Twin development approach***

**Necessity**

Within DSOs, Digital Twin developers do not use a structured development approach. A structured approach to Digital Twin development ensures that all teams follow a consistent and coordinated process, reducing the risk of misalignment and overly complex models.

**Potential risks if not adhered to**

Without a documented approach, teams may follow different processes or overlook critical steps, leading to inconsistencies and variable redundancies in the Digital Twin's development. This could result in a Digital Twin that is not fit for purpose, overly complex and not understandable by the users. This could eventually lead to incorrect decisions being made based on Digital Twin outputs which could cause loss of life or injury to field workers, damage to electrical infrastructure, financial loss and/or loss of electrical power network reliability. Table 13 shows how the loss scenario can potentially lead to unsafe control actions, system-level hazards and losses.

**Minimal requirements**

- Develop a Digital Twin development approach that outlines each phase of the project, preconditions and the purpose of the Digital Twin, key deliverables, and responsibilities.
- Ensure that the development approach is accessible to all relevant teams and regularly updated based on lessons learned.

**Acknowledging the risk**

There may be scenarios where documenting a structured development approach is not possible due to the complexity of the project, unforeseen changes, or because the development has already started. In this case, the DSO should acknowledge the risks associated with a less structured approach and focus on identifying weaknesses of the Digital Twin, caused by the unstructured development approach. When the Digital Twin has already became too complex (e.g.: redundant variables or multiple unclear purposes/outputs), risks can be mitigated by, for example, clarifying the visual representation of the Digital Twin.

*Table 13: Constraint C-14.1 preventing unsafe control actions, caused by specific loss scenario, and therefore system-level hazards and losses*

| Constraint | Loss scenario | Unsafe control action | System-level hazard | Loss |
|---|---|---|---|---|
| **C-14.1: Document a structured Digital Twin development approach** | **LS-14:** The Digital Twin development team does not use a structured development approach | **UCA-14.1:** Not having the preconditions of the Digital Twin clearly mapped out<br>**UCA-14.2:** Using redundant variables that do not improve the performance of the Digital Twin<br>**UCA-14.3:** Not having the purpose of the Digital Twin clear before the development of the Digital Twin | **H-5:** Overly complex Digital Twin models that are difficult to manage and understand | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |

2. ***C-14.2: Establish regulations and guidelines for teams/departments to adhere to the structured Digital Twin development approach***

**Necessity**

Within DSOs, Digital Twin developers do not use a structured development approach. Regulations and guidelines provide clear instructions and expectations for teams, ensuring that the structured approach to Digital Twin development is followed by everyone involved.

**Potential risks if not adhered to**

Without a documented approach, teams may follow different processes or overlook critical steps, leading to inconsistencies and variable redundancies in the Digital Twin's development. This could result in a Digital Twin that is not fit for purpose, overly complex and not understandable by the users. This could eventually lead to incorrect decisions being made based on Digital Twin outputs which could cause loss of life or injury to field workers, damage to electrical infrastructure, financial loss and/or loss of electrical power network reliability. Table 14 shows how the loss scenario can potentially lead to unsafe control actions, system-level hazards and losses.

**Minimal requirements**

- Develop detailed guidelines that outline the processes and standards that each team must follow during Digital Twin development.
- Implement compliance checks and reviews to ensure that all teams adhere to these guidelines.

- Provide training and support to teams to help them understand and implement the development approach for models like Digital Twins.

**Acknowledging the risk**

There may be scenarios where there is no time or resources to establish regulations and guidelines. It might also be possible that teams do not adhere to the established guidelines due to unforeseen challenges. Also in this case, the DSO should acknowledge the risks associated with a less structured approach and focus on identifying weaknesses of the Digital Twin, caused by the unstructured development approach. When the Digital Twin has already became too complex (e.g.: redundant variables or multiple unclear purposes/outputs), risks can be mitigated by, for example, clarifying the visual representation of the Digital Twin.

*Table 14: Constraint C-14.2 preventing unsafe control actions, caused by specific loss scenario, and therefore system-level hazards and losses*

| Constraint | Loss scenario | Unsafe control action | System-level hazard | Loss |
|---|---|---|---|---|
| **C-14.2: Establish regulations and guidelines for teams/departments to adhere to the structured Digital Twin development approach** | **LS-14:** The Digital Twin development team does not use a structured development approach | **UCA-14.1:** Not having the preconditions of the Digital Twin clearly mapped out<br>**UCA-14.2:** Using redundant variables that do not improve the performance of the Digital Twin<br>**UCA-14.3:** Not having the purpose of the Digital Twin clear before the development of the Digital Twin | **H-5:** Overly complex Digital Twin models that are difficult to manage and understand | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |

***C-16.1: Establish collaborative objectives aimed at system integration between different relevant departments***

**Necessity**

Withing DSOs, departments (such as IT/OT structures) are hesitant to collaborate on the implementation and operation of Digital Twins. Collaborative objectives are needed to ensure that all relevant departments within a DSO (such as IT, OT, and asset management) work towards the same goal of system integration. Without clear objectives, efforts can become fragmented, leading to inconsistencies in how data and systems are integrated.

**Potential risks if not adhered to**

If collaborative objectives are not established, there may be a lack of alignment between departments, resulting in ambiguous or inaccurate system integration. This could lead to a Digital Twin that fails to accurately represent the physical grid, potentially causing misinformed decisions. Incorrect decisions being made based on Digital Twin outputs could cause loss of life or injury to field workers, damage to electrical infrastructure, financial loss and/or loss of electrical power network reliability. Table 15 shows how the loss scenario can potentially lead to unsafe control actions, system-level hazards and losses.

**Minimal requirements**

- Develop a cross-departmental integration plan with clearly defined roles and responsibilities.
- Regularly update and review objectives to ensure ongoing alignment and adaptation to new challenges.
- Implement a governance structure to oversee and facilitate collaboration.

**Acknowledging the risk**

Even with collaborative objectives, there may be instances where alignment between departments is challenging to achieve. In such cases, it is important to recognise the limitations and manage the risks associated with potential misalignments. DSOs could implement validation processes to catch and address inconsistencies in system integration for Digital Twins early, to ensure that the Digital Twin remains a reliable tool despite these challenges.

*Table 15: Constraint C-16.1 preventing unsafe control actions, caused by specific loss scenario, and therefore system-level hazards and losses*

| Constraint | Loss scenario | Unsafe control action | System-level hazard | Loss |
|---|---|---|---|---|
| **C-16.1: Establish collaborative objectives aimed at system integration between different relevant departments** | **LS-16:** Departments are hesitant to collaborate on the implementation and operation of Digital Twins | **UCA-16.1:** Departments/teams work siloed | **H-3:** Inaccurate Digital Twin models<br>**H-4:** Ambiguous Digital Twin representations | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |

# 6 Discussion

This chapter will discuss the research, by reflecting on the results and investigating why these specific findings occurred. This chapter will also reflect on how this research will contribute socially and managerially. Additionally, the research will be situated within the broader literature and suggestions for further research will be made. Finally, the limitations of the used methodology will be shared.

## 6.1 Reflection on the results

The results of this research show how certain constraints can contribute to the safety of the grid and the people around it, regarding the implementation and operation of Digital Twins within a DSO. However, it should be mentioned that every DSO has challenges with regard to Digital Twins and system safety, that emerge more strongly or have greater priority than other DSOs. Despite the fact that this study was conducted for two different DSOs, the findings are not generalisable over all DSOs within the Netherlands. However, it was noticeable that there was very little distinction between the results of interviews within the two different DSOs. Additionally, it was observed that after nine interview, theoretical saturation occurred. The results of the last interview did not reveal new insights or themes.

Regarding the results of the literature review, it was noticeable that the publications focus mainly on factors that directly affect the (technical) performance of the algorithms and methods used. This is not a surprising result, given that other research also addresses how computational formulation analysis, model objectives, and input data and variables are given priority in AI system development (Dobbe, 2022). This research therefore highlighted that single (technical) components should not be separately analysed to evaluate the safety of the entire grid and the people around it, since safety is an emergent property (Leveson, 2012).

Another interesting finding is that Figure 6 shows that many technical and process-related statements were made during the interviews, in comparison with institutional statements. One reason may be that many regulations are taken as given and DSOs are used to taking them into account. Within a DSO, for example, privacy-sensitive information is something that employees often deal with, so they are familiar with the rules involved. However, it was still important to identify these laws and regulations in this study, especially since technological innovations may involve new laws and regulations.

## 6.2 Social and managerial relevance

From a social perspective, the use of different Digital Twin applications can contribute to solving the problem surrounding grid congestion. This research can help facilitate the implementation and operation of various Digital Twin applications by providing a generic overview of relevant technical implications, processes, laws and regulations, stakeholder involvement, and cooperation within a Dutch DSO. Examples of types of Digital Twins that can contribute to the grid congestion problem and that are mentioned in the literature and interviews, are mainly focused on demand forecasting (Xie et al., 2019), asset management (Fernandes et al., 2022), and predictive maintenance (interviewee 2 & 3).

In addition, a Digital Twin can also improve the efficiency of certain processes within a DSO, allowing current employees to focus on other concerns and tasks. This is an attractive side benefit, given the shortage of workers within DSOs (interviewee 4 & 6). Moreover, this research can contribute to the system safety of the grid and the people around it. First, by incorporating the recommended interventions (section 5.7) and overall recommendations (section 8) of this research and improving system safety while implementing and using Digital Twins. These recommendations will help prevent eventual system-level losses. Second, DSOs can use this STPA-inspired analysis as an example for a structured way of thinking ahead from their challenges to possible system-level hazards, with the goal of avoiding undesirable situations.

## 6.3 Academic reflection and future research

This research contributes academically by firstly approaching the safe implementation and operation of Digital Twins for the electricity grid in a holistic manner, instead of highlighting mainly technical aspects, as has been done in most research on Digital Twins for electricity grids (chapter 3). Additionally, this study tackles the application of Digital Twins in the electrical grid from a perspective of system safety, which is likewise not given much consideration in the literature.

This STPA-inspired analysis, in addition to providing a guideline for DSOs as mentioned in previous section, can also provide inspiration for further research for similar models in different domains. Leveson and Thomas (2018) identify the system-level constraints at the start of the analysis, ultimately devising loss scenarios that can lead to system-level hazards. The STPA-inspired analysis in this study approaches it the other way around and first identifies weaknesses and challenges within the system (loss scenarios), to find out to which potential unsafe control actions this might lead, from which constraints are eventually drawn up. This is an innovative approach, designed to establish safety constraints for (new) AI models within the design phase. This helps to alert a developer early on to the potential repercussions and risks associated with challenges related to implementing and operating a model into practice.

However, while the research provided interesting insights, some aspects of the research questions could benefit from further exploration. This research approaches the safe implementation and operation of Digital Twins in a holistic manner. This has led to many different loss scenarios and controller constraints being identified, not all of which have been discussed in depth. Future research could further investigate these loss scenarios and controller constraints, for example using a Digital Twin case study within a Dutch DSO, to determine the relative importance of the constraints. In addition, further research could also examine specific tools for the constraints. The constraints are now formulated in fairly general terms, so research into, for example, the most effective tool for a particular constraint would be useful.

## 6.4 CoSEM alignment

This research aligns with the MSc Complex Systems Engineering program, due to the socio-technical approach of the problem. The research concerns Digital Twins, a technical innovation, in the power distribution environment that involves a complex infrastructure. In addition, the problem is approached from three different viewpoints, namely from a technical, institutional and process perspective. Thus, during the research, the technical features of the Digital Twin, the processes involved, the power grid infrastructure itself, existing regulations, as well as different interests and interactions between stakeholders have been considered. Finally, a framework has been developed in which all elements come together, to get a general understanding of how the system functions and to make recommendations based on the findings.

## 6.5 Limitations and future research

It is important to recognise some limitations even though the selected research methods provide a solid approach for exploring Digital Twins in the power distribution industry. First, qualitative analyses like interviews have explanatory limitation in that they are essentially heuristic in nature rather than definitive (Knight, 2001b). Although the results are detailed, the empirical rigor may be limited. This could imply that slightly different results would be produced if this study would be conducted again.

Furthermore, selection bias may be the case by relying on interviews within two different DSOs for empirical insights because the DSOs selected may not accurately reflect the diversity of the whole power distribution industry in the Netherlands. However, the interviewing of Digital Twin experts will minimise this bias in selection. This is due to the fact that the Digital Twin experts have experience in working with different DSOs, providing a complete overview of all potential opportunities and challenges. Still, due to time constraints, the scope of the interviews was limited to nine participants. This might not fully cover the diversity of perspectives within the whole DSO. Future research could focus on interviewing a larger and more diverse audience to improve the generalisability of the results. The internal validity of the study can also be increased by conducting an abductive follow-up study, which examines how the loss scenarios lead to system-level hazards. The system-level hazards are based on a combination of the results of the literature study, the interviews and logical reasoning. Validity would improve if these relationships were explored in more depth.

While the STPA-inspired analysis is used for structuring heterogeneous data from the literature review and interviews, it may also present difficulties. A structured and clear approach was used, specific coding and categorisations were used for organising data to ensure consistency (Knight, 2001b). By using coding methods consistently across all the collected information, the data could be compared in a structured manner.

Another limitation of this research is the use of an STPA-inspired analysis rather than the full STPA (System-Theoretic Process Analysis) methodology. While this approach was more suited to the context of Digital Twin implementation and operation, it may lack the depth and rigor of the original STPA. This method was chosen because it explores the unsafe control actions that might be caused by the identified challenges, though it might not carry the same credibility among experts familiar with the full STPA, potentially affecting the acceptance of the safety analysis and recommendations in this thesis.

# 7 Conclusion

Digital Twins are a promising solution to reduce grid congestion and improve the resilience of power distribution systems in the Netherlands. Digital Twins are virtual representations of physical assets within the grid, enabling real-time monitoring, analysis, and optimisation of network performance (Botín-Sanabria et al., 2022). By simulating various scenarios and predicting potential congestion, Digital Twins can empower operators to manage grid operations and prevent disruptions. This research, using a qualitative approach through process, technical, and institutional perspectives, provides a comprehensive framework to guide the safe implementation and operation of Digital Twins for power Distribution System Operators (DSOs), answering the main research question:

*What are the key system safety factors for a Distribution System Operator to consider for the implementation and operation of a Digital Twin?*

Key findings from the literature review and the interviews show the important role of technical safety factors like system and data integration, data quality and integrity, as well as the need for standardised protocols. Several technical challenges are identified, such as the complexity of integrating IT and OT systems, the need for continuous data validation, and the importance of clear contractual agreements among stakeholders to avoid overly complex models. Moreover, the research shows the importance of a structured development approach for Digital Twins. Design decision, such as a well-defined scope and boundary constraints, influence the final output of the Digital Twin. Additionally, collaboration within DSOs and with external stakeholders, including IT firms and regulatory bodies, also affect the implementation and operations of Digital Twins.

A System-Theoretic Process Analysis (STPA)-inspired approach is conducted to identify constraints to prevent system-level hazards caused by the challenges. The identified challenges might lead to unsafe control actions, and eventually to one or more of the following system-level hazards: unauthorised access to sensitive data by external third parties, Digital Twins not complying to identified industry protocols, safety laws and regulations, inaccurate, ambiguous and/or overly complex Digital Twin models, and/or Digital Twin failure caused by lack of computational power

By using this analysis, system safety aspects can be structured by identifying potential hazards, loss scenarios, unsafe control actions and finally constraints within the complex power system. The research finally provides a comprehensive framework, namely a system safety control structure, identifying all relevant constraints to ensure system safety of the Digital Twin, the grid, and the people around it.

In conclusion, this study provides a holistic approach, identifying socio-technical factors influencing the safe implementation and operation of Digital Twins in the power distribution sector. The proposed framework, a safety control structure, serves as a practical guide for DSOs to guide them for a safe implementation of Digital Twins. Moreover, this study shows how an STPA-inspired analysis can be used to analyse and enhance the system safety of AI models.

# 8 Recommendations

Based on this research, both substantive recommendations on the safe implementation and operation of Digital Twins, as well as next steps based on this research are explained. First, the safety control structure in Figure 9 can be used to see which constraints can be useful for the discovered challenges within the relevant DSO. It can be generally analysed which constraints are effective within a specific DSO and which constraints can therefore be implemented. The constraints that are considered useful can be further analysed and specialised so that they fit within the relevant DSO.

Based on the most recurring themes within the literature review, the interviews, the following more specific recommendations can also be made:

- Provide middleware and translation layers to facilitate system integration (5.7.2.1)
- Establish clear data taxonomy and data standards (5.7.2.2)
- Categorise and standardise data before using it as input for the Digital Twin (5.7.2.2)
- Document a structured Digital Twin development approach (5.7.2.3)
- Establish regulations and guidelines for teams/departments to adhere to the structured Digital Twin development approach (5.7.2.3)
- Establish collaborative objectives aimed at system integration between different relevant departments (5.7.2.3)

Zooming out, Figure 8 can also be used by a DSO to identify undiscovered or DSO-specific challenges for safe Digital Twin implementation and operation. By analysing the aggregated model, a DSO can discover where challenges and their potential system-level hazards lie. This complete overview can be used to see how certain control processes and data flows influence each other. The STPA-inspired analysis can then be used to map out associated controller constraints, to enhance/maintain the system safety of the grid, while using Digital Twins.
In addition, this analysis can also be used to map hazards for similar AI models. The approach used in this research is namely a reasoning from implementation and operational challenges for new technologies, to set constraints from here and integrate safety in the design phase.

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# 10 Appendices

## Appendix A: Literature review findings

*Table 16: Results from mapping literature review*

| Literature review | | | |
|---|---|---|---|
| **Author** | **Title** | **Digital Twin type** | **Social and scientific relevance** |
| **1. Xie et al. (2019)** | A neural ordinary differential equations based approach for demand forecasting within power grid Digital Twins | The output of the network is efficiently computed via a black-box ordinary differential equation (ODE) solver | Facilitates demand forecasting |
| **2. Zhan et al. (2020)** | Power Distribution Network Based on Digital 3D Twin Panoramic Modelling | Digital 3D twin panorama modelling | Calculate the line loss of the power distribution network, so that the accuracy is guaranteed |
| **3. Moutis and Alizadeh-Mousavi (2021)** | Digital Twin of Distribution Power Transformer for Real-Time Monitoring of Medium Voltage from Low Voltage Measurements | Real-time monitoring: taking measurements of voltage and current on the low-voltage and medium-voltage side of the T/F | Monitor the medium-voltage side waveforms of distribution system transformers, to improve the visibility of operators into distribution system |
| **4. Gao and He (2021)** | Power supply line selection decision system for new energy distribution network enterprises based on digital twinning | Tool consisting of both hardware (consisting of decision-maker, processor, and data collector) and software | A new decision system of power supply line selection for new energy distribution network enterprises |
| **5. Fernandes et al. (2022)** | Digital Twin Concept Developing on an Electrical Distribution System—An Application Case | 3D virtual replica of existing physical objects and real-time monitoring of certain measures: network virtual maps, 3D asset models, dynamic and real-time data of grid assets, and IoT Sensing | Different applications of network Digital Twins and their potential benefits in the electrical power sector |
| **6. Bulatov et al. (2022)** | Digital Twin Formation Method for Distributed Generation Plants of Cyber–Physical Power Supply Systems | Digital Twin based on experimental data using hierarchical fuzzy systems | Virtual representation of the automatic regulation system within distributed generation plants, with a specific focus on voltage and rotor speed |

| | | | |
|---|---|---|---|
| | | | control, contributing to improved understanding and performance of the overall power supply system |
| **7. Söderäng et al. (2022)** | Development of a digital twin for real-time simulation of a combustion engine-based power plant with battery storage and grid coupling | A fast-running model (FRM), coupled with a complete power plant control model. Real-time functions are tested on a dedicated rapid-prototyping system using a target computer. | Coordinated control of combustion engine-based power plants with battery storage for optimising renewable energy |
| **8. Bai and Wang (2022)** | Digital power grid based on digital twin: Definition, structure and key technologies | Key technologies explained: Intelligent sensing technology, Heterogeneous communication technology, Data centre technology, Digital power grid model, Power intelligent brain, Digital business operation | Elaborating on different technologies of digital power grids |
| **9. Wang et al. (2023)** | Consensus control for distributed power tracking by device-level digital twin agents | Device-level-based digital twins to monitor physical signals for computer-aided design for power tracking | The combination of the proposed distributed power tracking method and communication network can accelerate computational efficiency and protect the privacy of the regulation resources |
| **10. Heluany and Gkioulos (2023)** | A review on digital twins for power generation and distribution | Discussing different Digital Twin technologies | To enhance distribution management |
| **11. Nasiri and Kavousi-Fard (2023)** | A Digital Twin-Based System to Manage the Energy Hub and Enhance the Electrical Grid Resiliency | Digital Twin-based real-time analysis | To meditate the power system vulnerability whenever cascading failures and blackouts occur for any reason, to improve the resiliency |
| **12. Leopold et al. (2023)** | An interoperable Digital Twin to simulate spatio-temporal photovoltaic power output and | Digital Twin based on Free and Open-Source software and geospatial software technologies | To analyse renewable energy production in urban areas and cities for |

| | | | |
|---|---|---|---|
| | grid congestion at neighbourhood and city levels in Luxembourg | in the simulation, monitoring, and management of renewable-based energy systems | decarbonisation and reduction of climate change impacts |
| **13. Yin et al. (2024)** | Digital twin-driven identification of fault situation in distribution networks connected to distributed wind power | Fault situation identification framework: a high-precision digital twin avatar with parallel strategies of fully electromagnetic transient calculation and a skip-connected dilated causal convolution | Identification of fault situation in distribution networks connected to distributed wind power |
| **14. Li et al. (2023)** | Distributed Power Grid Connected Panoramic Perception Technology Based on Digital Twin Model | Clustering screening of Proton-exchange membrane fuel cell grid connected status variables | To enhance monitoring large-scale distributed Proton-exchange membrane fuel cell grid-connected operation status |

## Appendix B: Guiding questions semi-structured interview

**Digital Twin in general**

- What is your experience with Digital Twins?
- How do you see the role of Digital Twins developing in the distribution network sector?

**General system safety and dependency on Digital Twin**

- To what extent is the functioning of the network in your organisation dependent on the Digital Twin?
- What risks do these dependencies entail?
- What is being done or could be done to reduce these risks?

**Technical**

- Which technical features do you think are crucial for a reliable Digital Twin in managing the distribution network?
- What challenges have you encountered in integrating and maintaining a Digital Twin?

**Institutional**

- Which regulatory features do you think are crucial for a reliable Digital Twin in managing the distribution network?
- What regulatory challenges have you encountered when implementing Digital Twins, and how has your organisation dealt with them?

**Process**

- How do you work with other stakeholders to implement and optimise Digital Twins in your network?
- How do these authorities influence the system safety of the Digital Twin and the grid?

# Appendix C: Literature summary

**1. Guerreiro et al. (2024)**

In their research, Guerreiro et al. (2024) focus on the integration of large-scale wind power plants (WPPs) into the grid, exploring the use of Digital Twins to simulate and analyse grid compliance. The Digital Twin in this case, helps in forecasting and validating the performance of WPPs under specific grid conditions. According to Guerreiro et al. (2024), this enables a more accurate integration of WPPs and a more efficient energy distribution. In terms of maturity levels of the Digital Twin, Guerreiro et al. (2024) explain that levels 2, 3, 4, and 5 are still not extensively used in the grid integration components of Wind Turbine Generators (WTGs) and WPPs design and operation. According to Guerreiro et al. (2024) this is because of the increased automation of the data flow from the physical object to the Digital Twin, decision-making through Digital Twin handling becomes more independent. Acceptance of the more autonomous maturity level Digital Twins is typically challenging because WPPs are complex and vital infrastructures. Guerreiro et al. (2024) explain that it is more realistic to adopt Digital Twins with maturity level 4, where a certain amount of engineering assessment is built into the decision-making process to guarantee more reliable Digital Twin operations. However, according to Guerreiro et al. (2024), more standardisation of protocols, norms and guidelines that govern the implementation of Digital Twins, will be required for widespread implementation and operation.

**2. Wang et al. (2023)**

The research of Wang et al. (2023) describes the integration of different renewable energy resources by using Digital Twins for distributed power tracking within power grids. To simulate and control the behaviour and interactions of the physical renewable energy resources, virtual replicas are modelled.
The results of the experiments from Wang et al. (2023) show that the model has a high stability and accuracy and suggest that the research model has a functional value in power grid transformer prediction and life span assessment. However, only a fraction of the load conditions is taken into account when examining variations in transformer load rate (Wang et al., 2023). When transformers are actually in use, different complex situations arise. Due to the model's limitation in accounting for a limited portion of the load conditions, it may be possible to predict transformer health and remaining life incorrectly, which could result in premature failures or unanticipated downtime, endangering the safety of the system.

**3. Yin et al. (2024)**

Yin et al. (2024) describes a Digital Twin framework that identifies fault situations in distribution networks with distributed wind power. This paper aims to overcome the current obstacles of offline post-event analysis and asynchronous online fault identification by presenting a new fault situation identification Digital Twin.
In their paper, Yin et al. (2024) show the high accuracy and ultra-real-time processing through electromagnetic transient modelling and parallel computing. Additionally, they demonstrate robust fault identification methods that preserve accuracy despite noise and data loss. However, the article does not address how the system manages for example high data volumes and integration with existing infrastructure.

**4. Leopold et al. (2023)**

The purpose of the Digital Twin of Leopold et al. (2023) is to model grid congestion and photovoltaic (PV) power output at the local and municipal levels in Luxembourg. By integrating high-resolution data to optimise PV installation and energy production, the Digital Twin aims to support urban energy planning and therefore support Luxembourg's decarbonisation and climate change measures. The research of Leopold et al. (2023) shows how interoperable geographical Digital Twins, built using geospatial software technologies and open-source software, can be used to simulate, monitor and manage renewable energy systems.

Leopold et al. (2023) explain the benefits of using interoperable geographical Digital Twins as platforms to support the transition to renewable energy resources. The Digital Twin uses open-source technologies, standards, and APIs to integrate data and simulation tools. However, the authors do not go into detail about specific safety protocols or challenges in data security and reliability within these open and interoperable systems. They also do not address the consequences of potential modelling errors or the necessity to regulate the difference between simulated predictions and real-world outcomes.

**5. Gao and He (2021)**

The Digital Twin investigated by Gao and He (2021) is aimed at improving the decision-making process for selecting power supply lines in new energy distribution networks. This Digital Twin technology is used to create a real-time simulation model that assists in the analysis of different line selection scenarios, based on the changing network conditions and load demands.

The system's performance has been determined by the authors from both experimental and theoretical perspectives (Gao & He, 2021). However, there is no discussion of what problems it can cause if, for example, the input data of the model is incorrect.

**6. Li et al. (2023)**

The function of the Digital Twin explained by Li et al. (2023) is to improve monitoring and predictive analysis of the operation status of large-scale distributed Proton-Exchange Membrane Fuel Cell (PEMFC) grid connections.

The authors Li et al. (2023) conclude that the key metrics used to evaluate the performance of the model, all increase when the used dataset increases. A reliance on significant data inputs could be hazardous when there is poor data quality or when there is less data available. Moreover, the clustering algorithms' running times and memory demands also increase with the volume of data (Li et al., 2023). In particular, during crucial operations or peak loads, this can result in processing delays and possible system overload, which might compromise the Digital Twin's reliability.

**7. Nasiri and Kavousi-Fard (2023)**

The article of Nasiri and Kavousi-Fard (2023) discusses a Digital Twin based on real-time data analysis, designed to increase resiliency when mitigating power system vulnerability during cascading failures and blackouts that may arise for any reason. Furthermore, a water-power package is suggested in order to increase the system's vulnerable percentage by immediately supplying energy to the grid in the event of a line or generator outage. In order to examine the online vulnerability data that results from a corresponding physical twin in real-time, Nasiri and Kavousi-Fard (2023) develop a Digital Twin model and a cloud platform created by the Amazon Cloud Service (ACS) into the Amazon Web.

As long as the data entered for both twins are the same, the online digital analysis of the system may be used to precisely verify the real system and make an informed decision at the right moment (Nasiri and Kavousi-Fard, 2023). Compared to the other articles, Nasiri and Kavousi-Fard (2023) consider that it is essential to be aware of the uncertain inputs for the system's real-time analysis. In order to simulate the inputs, including the load demands across the grid, Nasiri and Kavousi-Fard (2023) suggest a coefficient model that was derived from the unscented transformation (UT)-based uncertainty model. Furthermore, they applied the suggested uncertainty model to the inputs.

**8. Söderäng et al. (2022)**

The Digital Twin developed by Söderäng et al. (2022) is used for real-time simulation of a combustion engine-based power plant integrated with battery storage and grid coupling. The goal of the Digital Twin is to optimise the operational efficiency and responsiveness of power generation, particularly for managing dynamic grid demand and improving the integration of renewable energy sources.

Regarding the safety of the Digital Twin, Söderäng et al. (2022) exclusively focus on the accuracy of the models. Other aspects, including interface with other systems, should be investigated in order to truly apply the Digital Twin.

**9. Bulatov et al. (2022)**

The focus of the research of Bulatov et al. (2022) is on developing a process for creating Digital Twins for distributed generation (DG) plants, that are a component of cyber-physical power supply systems. They consider a technique for creating a Digital Twin of a system that automatically controls a synchronous generator’s voltage and rotor speed. Using experimental data, the architecture of the Digital Twin is given as a multiply connected model.

The successful creation of a neuro-fuzzy model for a Digital Twin in a DG plant is highlighted in the conclusion, showing high precision and low variance from experimental data. This demonstrates the model's dependability and practical usefulness for precisely replicating the various DG plant components. However, Bulatov et al. (2022) do not address issues related to scalability, integration with larger systems, and performance under changing conditions, which is important for the safety of the grid. Bulatov et al. (2022) do mention limitations in model complexity and flexibility that currently exist and emphasise the need for additional research and improvement of the Digital Twin.

**10. Fernandes et al. (2022)**

In order to improve asset management, safety, and operational efficiency in electrical distribution systems, this paper of Fernandes et al. (2022) addresses the best practices for developing a Digital Twin. In order to improve workforce operations, the Digital Twin provides real-time monitoring and control capabilities and integrates with virtual reality (VR) and augmented reality (AR).

Fernandes et al. (2022) indicate that their Digital Twin is applicable and relevant in the electrical sector to a certain measure. The development and application of the Digital Twin, however, may present difficulties that could compromise system safety. The authors draw attention to the need for high-quality equipment and the complex process of image processing required to produce a functional Digital Twin. In fact, these aspects are critical because they affect the Digital Twin's accuracy and reliability, which also affects the decision-making and operational safety of the power distribution network. Additionally, the outcome of the Digital Twin depends on smartphone photos made by a field inspector, to be examined in 3D by another inspector. However, if the photo is misrepresented, it could put another inspector at risk. While Fernandes et al. (2022) acknowledge that these issues must be resolved in order for the Digital Twin to be applied in the industry, they offer no specific solutions in the article.

**11. Moutis and Alizadeh-Mousavi (2021)**

The research of Moutis and Alizadeh-Mousavi (2021) investigates the need for real-time monitoring of power distribution systems, which has become increasingly important due to the deregulation of electricity markets, and the growth of renewable energy sources. According to the authors, real-time data on voltage and current are essential for managing the stability of the power grid. The Digital Twin explained in the article uses a mathematical model of the distribution transformer to calculate waveforms of the medium voltage sides in real-time, using their low voltage side measurements.

Moutis and Alizadeh-Mousavi (2021) demonstrate high calculation accuracy, which successfully captures harmonic content and system errors. Higher sampling rates of the input low voltage waveforms improve the accuracy of the Digital Twin and match the performance of traditional instrument transformers. Other methods include field deployment on a distribution system monitoring device to evaluate its performance in real-world conditions, including considerations of installation costs and operational disruptions. The authors also point out some shortcomings and directions for future studies. In particular, when there are compensated medium voltage ground faults, the Digital Twin is not able to precisely determine phase voltages unless the primary and secondary windings of the transformer are both grounded. This restriction may make it more difficult to completely determine the type of faults occurring in a given situation. Furthermore, even though the technique is ready to be expanded to monitor medium-voltage to high-voltage transformers, this expansion is still theoretical and would require extensive testing to verify its feasibility and effectiveness in improving grid monitoring.

**12. Zhan et al. (2020)**

In the article of Zhan et al. (2020), a 3D Digital Twin is introduced, of panorama modelling in electricity distribution networks. The authors calculate the line loss of the electricity distribution network, using the average current approach. The grid system is optimised using the 3D panoramic modelling approach, and the electricity distribution network is calculated using a data structure. Zhan et al. (2020) first examine the topological structure, after which they determine the line loss calculation method.

Regarding the safety of the implementation of the Digital Twin, the authors mention the preliminary checks which are conducted to optimise unreasonable data, before using the power engine to construct the 3D grid. Additionally, they explain the Level of Detail Model Technology (LOD), which is a rendering technology to simplify the complexity of 3D models by adjusting the level of detail, according to the size and distance to the model from the viewer. Zhan et al. (2020) show that the method leads to a 17% increase in the rendering efficiency of the distribution grid results. However, the limitations or risks of using this simplification method in real-life are not pointed out.

**13. Xie et al. (2019)**

Xie et al. (2019) describe a neural Ordinary Differential Equations (ODE) based Digital Twin model for demand forecasting within power grids. The model is capable of generating short-term load forecasting by integrating deep learning with dynamical systems theory, specifically for residential power load forecasting. The method demonstrates handling real-world data effectively, by using a household-level benchmark dataset.
The authors suggest that to be able to use the Digital Twin in real-life, the model needs to be generalised and needs the integration of exogenous factors. Furthermore, it needs to be studied how model depth will influence prediction errors. These analyses will make it possible to control physical assets that belong to various energy vectors within the Digital Twin, by using prediction algorithms.

# Appendix D: Summaries of interviews

## Interviewee 1

### Background

Interviewee 1 is a systems strategist within DSO 1 and is concerned with electricity systems of the future. He is an Asset Management expert and thinks about strategies for the entire power grid.

### Summary

According to interviewee 1, the Digital Twin is a computer simulation of the grid, which allows you to do various tests that you would not perform in the physical grid because these tests could endanger the grid.

DSO 1 is currently working together with research institutions on a real-time digital simulator, with hardware in the loop. This Digital Twin shows whether power protection is switching correctly, based on voltage and currents calculated. The Digital Twin can also show how this affects the rest of the grid.

Interviewee 1 explains that rapid phenomena are currently being researched within DSO 1, where the Digital Twin functions as a new type of power protection. If behaviour within the network changes, the Digital Twin will detect it and switching can be done based on this fact. On the other hand, according to interviewee 1, there are also opportunities around phenomena with a larger time step, i.e., not real-time.

A useful Digital Twin, according to interviewee 1, would be one to which you could also connect physical hardware, so that much of the grid is digitally simulated and executed. The Digital Twin could then control the grid based on the data received, after which the Digital Twin in turn receives feedback from the grid. So when a dynamic load flow analysis is performed, for example, according to interviewee 1, differential equations can be used to model how the power grid reacts to changes or disruptions in the grid.

Interviewee 1 thinks a Digital Twin can also be applied as a training target. For example, undesirable situations, such as cyber-attacks, can be simulated. In this way, employees can be trained or tested on how to handle this situation.

Another application that interviewee 1 mentions is testing on a Digital Twin, what impact it has on the grid if components are overloaded temporarily and operated more to the limit. Interviewee 1 mentions dynamic line rating as an example. Interviewee 1 mentions that before developing the Digital Twin, it is important to consider the exact question that the Digital Twin should meet and what kind of requirements the Digital Twin has (e.g., what time steps do you want to use in your simulation). Also, according to interviewee 1, the scenario where so many variables are modelled that the model can no longer be comprehended should be avoided. Interviewee 1 explains that careful consideration must be given to simplifying the model, also with a view to the computing capacity of the systems.

According to interviewee 1, it is important to realise that the Digital Twin only models based on input. For example, if some phenomena of component deterioration are not modelled along, their effects will not be visible either. It is therefore important to think about which simplifications do not influence the effect being examined.

Interviewee 1 explains that DSO 1 collaborates a lot with other stakeholders. It is important that the models are exchanged confidentially. Agreements must be made about who may use and view the Digital Twin, and how solutions will be handled. With respect to data confidentiality, dummy data could also be used if other stakeholders are involved.

Interviewee 1 also emphasises that it is important to make certain agreements, for example about programming languages. In addition, it is important to spend time understanding each other's "language," since different types of expertise can be far apart. This is important, for example, for the interpretability of the Digital Twin.

### Interviewee 2

**Background**

Interviewee 2 has experience with system and network strategies within DSO 1. Interviewee 2 is also involved in a European Digital Twin project and several projects related to active network management and active distribution systems in broad terms.

**Summary**

According to interviewee 2, there are already various Digital Twin application within DSO 1. Still, DSO 1 needs to take quite a number of steps to evolve them. These models are mainly about predictive maintenance. The models have insight into physical components of the grid, and the Digital Twin can be used to determine when assets need maintenance. The challenge is to interconnect different components.

Possible future Digital Twins, according to this interviewee, would deal with dynamic stability aspects, voltage monitoring, long-term planning, short-term planning, and operational planning. All these aspects integrated so that a "single source of truth" is achieved.

Interviewee 2 thinks that Digital Twins are going to play a major role in the future, regarding decision-making. The main challenge according to interviewee 2 is the interconnection of systems. So, the interface and specific data protocols between different components of the system, but also different entities. Another challenge according to the interviewee is interconnecting systems or models with different data standards. The interviewee also emphasises the challenge of having enough computational resources to run the models. When one ‘single source of truth’ is created, a lot of computational resources are needed. According to the interviewee, interpretability of the models also deserves some attention. A model might perform well, but if the model is not interpretable, this can be catastrophic. Interviewee 2 explains that the company structure is going to be more interdisciplinary when Digital Twins get involved. Departments need to work together to design, operate and maintain the Digital Twins. However, their functionalities differ, for example between using real-time data and using more historical data. The biggest challenge here is alignment between OT and IT structures because they are usually segregated. According to interviewee 2, it is also important to investigate data storage since data is getting more and more important.

### Interviewee 3

**Background**

Interviewee 3 works in the IT sector within DSO 1, focusing on digitalising strategies. This interviewee also has experience with asset management and IoT.

**Summary**

Within DSO 2 they are already working on the combination of sensors and models, which can measure the use of complex investment intensive assets for performance management, process optimalisation and predictive maintenance. They are now also working on usings sensors for transformers. These processes involve IoT experiments and the integration of data into existing systems like SCADA and EMS

Interviewee 3 explains how potential Digital Twins can integrate data for consistency checks, enabling advanced analytics such as regression and machine learning, optimising sensor placement, providing decision-support, and even prepare for more decentralised energy systems using a layered architecture.

Interviewee 3 mentions the IT and OT alignment as a technical Digital Twin implementation challenge. It is challenging to integrate IT systems, such as GIS and asset management, with OT systems, like SCADA and EMS. Additionally, it is challenging to integrate the legacy systems in the Digital Twin and make data usable for real-time decision-making, since data must be gathered from different sources. Interviewee 3 therefore suggests a data architecture that links primary and secondary asset data, sensor data and environmental data within one Digital Twin. Regarding the implementation of Digital Twins, DSOs also face financial limitations in investments in digital innovations. Interviewee 3 explains that the focus of the regulators is more on traditional asset investments instead of digital projects. The interviewee also states that the role of cloud providers, offering Digital Twin solutions, will grow. This evolution of technology from custom to product and service-based models will influence how DSOs adopt Digital Twins.

### Interviewee 4

#### Background

Interviewee 3 works at DSO 2 under system operations. This interviewee also has experience within the IT department within a DSO.

#### Summary

System operations within DSO 2 currently focuses on creating a digital representation of the grid to predict and solve operational problems and to finally improve the connection of customers to the network. According to interviewee 4, Digital Twins can be applied on a larger scale in the low-voltage grid to manage grid congestion caused by for example solar power generation. Ideally, the Digital Twin would also operate more autonomously to reduce the need for manual operations.

Interviewee 4 mentions a technical Digital Twin implementation issue, namely the lack of adequate measurements in the low-voltage grid. According to this interviewee, there is a lack of sensors due to regulatory restrictions, high implementation costs, and a lack of manpower. The interviewee explains that there are enough anonymisation methods to anonymise the sensor data. Another challenge interviewee 4 mentions is that developing a complex system like a Digital Twin, asks for close collaboration between multiple teams and departments. According to this interviewee, a lack of cooperation can lead to inefficiency and errors during the development of the Digital Twin.

According to interviewee 4, more measurements would improve data validation. Interviewee 4 also reports that better cooperation with other DSOs and IT firms could improve the functioning of systems such as Digital Twins. This way you can learn from each other’s mistakes and use open-source solutions and shared developments.

According to interviewee 4, a micro-architecture is used, via an integration structure, which allows each team to focus on a specific task. The interviewee also explains that cloud solutions and databases are used, but that they would like to work more closely with IT firms to improve processes.

### Interviewee 5

**Background**

Interviewee 5 is a product owner within a software development team at DSO 2. This interviewee is responsible for a part of a Digital Twin, related to the grid model domain.

**Summary**

The team of interviewee 5 currently works on a near real-time model of the grid, which integrates different domains like measurements, network, regulation, and market domains. Using this model, the team can facilitate congestion management and flexibility contracts. According to interviewee 5, this model collects data from different systems and sources, generates context and makes predictions. Based on this model, both manual and autonomous actions are performed. Interviewee 5 explains that Digital Twins can be used to explore how the capacity of the grid can be maximised, to solve grid congestion and connection problems and to eventually ensure reliability of the grid.

Interviewee 5 explains how data integration can be a challenge, when trying to integrate different information domains (grid, telemetry, forecasting, limits, and market actions) into one Digital Twin model. This can also be challenging, according to the interviewee, considering the collaboration needed among fifteen tightly coupled teams. The interviewee explains that this type of collaboration requires a microservice architecture and deployment and release cycles. As stated by the interviewee, concerning the integration of different systems for Digital Twin development, it is important that all information systems use a consistent model to avoid ambiguities in interpretation of the model.

According to interviewee 5, the DSO works closely together with other DSOs and IT firms on different digitalisation projects. Since all DSOs in the Netherlands have the same problem and goal (resolving grid congestion), as explained by interviewee 5, it is relevant to collaborate on innovations such as Digital Twins to solve this problem. According to the interviewee, there is a separate organisational structure, in which different teams focus on their own tasks.

### Interviewee 6

**Background**

Interviewee 6 works within Asset Operations at DSO 2 and is an expert in the field of electrical power engineering and grid digitalisation and operation.

**Summary**

According to interviewee 6, DSO 2 mainly works on conducting Digital Twin models conducting what-if analyses to assess the impact of for example increasing electric vehicle penetration and integrating solar panels, heat pumps and industry electrification on the grid. These applications vary from simple data collection to complex autonomous operations, but according to interviewee 6 this depends on the specific use case. Interviewee 6 explains that it would be beneficial to improve real-time monitoring and controlling capabilities, using a Digital Twin. This could eventually partially replace experience-based and human-based analyses. The interviewee states that it is important to have a balance between automated processes and interventions of human experts. The interviewee mentions that implementing sensors for Digital Twin operations across millions of cables is very labour-intensive and costly, which could be a challenge for input data of the Digital Twin. According to interviewee 6, legal restrictions hinder using smart meter data from households to extent the data collections. Interviewee 6 also explains that there is a shortage of skilled personnel in the Dutch job market, which impacts the Digital Twin implementation. Within the DSO, employees are also struggling with the shift from traditional methods to digital solutions like Digital Twins, which makes collaboration between departments challenging.

In order to install more meters and use the data, interviewee 6 thinks it is possible to substantiate that smart meter data can be used in a safe and confidential manner, since the benefits outweigh the risks. According to interviewee 6 there are different layers of separation and collaboration between IT and OT to ensure safety.

### Interviewee 7

#### Background

Interviewee 7 is a Digital Twin expert and works at a consultancy firm and has experience in multiple DSO projects related to Digital Twins. This interviewee is currently involved in setting up data solutions that represent the electricity grid at DSO 2.

#### Summary

According to interviewee 7, the current focus of DSOs is on creating an “as-is twin” to get insight in the current state of the grid. Interviewee 7 explains that a Digital Twin collects data from Enterprise Asset Management Systems (EAMSs) (1D), GIS (2D) and 3D models to integrate them in a 4D model that also includes the lifecycle of assets. As stated by interviewee 7, the goal is to develop Digital Twins for different voltage levels and make sure they are interoperable. This will create a “single source of truth” for asset information that can be used for different use cases (asset performance management, condition-based maintenance, and predictive maintenance) and within different departments.

Interviewee 7 explains that to make systems (within a DSO and between DSOs and other stakeholders) interoperable, data standardisation is needed, which is a challenge within DSOs. Especially in the low-voltage grid, data inconsistencies are common, and data is often not correctly linked to specific assets. According to interviewee 7, historical data is often incomplete or inaccurate and improving the quality of the data is a challenge because of the decentralised operations of DSOs. Asset data lacks standardised categorisation and taxonomies. It is a challenge to solve this, according to the interviewee, because the organisational culture is separated, which has resulted in siloed information systems.

Interviewee 7 suggests working on improving data governance and master data management to standardise and categorise data and carry out continuous data quality checks. Interviewee also explains the importance of making sure that all relevant data is accessible to everyone who needs it. The interviewee also suggests implementing a data layer that can collect and integrate data from different systems, like SCADA, DMS, OMS and EAMS.

### Interviewee 8

#### Background

Interviewee 8 is a Digital Twin expert and works at a consultancy firm. This interviewee focuses on system operations, digital operations, and system flexibility in the electricity sector.

#### Summary

Interviewee 8 explains that Digital Twins within the electricity sector can cover a lot of different applications, such as grid simulation, load and power flow, short circuit analysis, optimisation based on load forecasts, weather forecasts and generation forecasts. Interviewee 8 expects that future Digital Twins will focus on condition-based maintenance to avoid over-maintenance and to predict potential issues.

According to interviewee 8, different departments within a DSO use Digital Twins for asset management, IT, OT, field operations and planning. However, these systems (like SCADA, GIS, and other simulation tools) are often not connected and interoperable. It is also challenging to ensure data accuracy and real-time updates from different systems. A data layer that can pull data from different sources could be a solution to this problem.

Interviewee 8 also explains the challenge of incorporating contractual constraints in the Digital Twin models, besides operational data. Interviewee 8 stresses the importance of processes like digital threads, to improve the interoperability between different systems (IT and OT) and departments. The interviewee also suggests educating engineers about contractual aspects the bridge the gap between technical and legal knowledge.

According to interviewee 8, DSOs are hiring software engineers from IT firms to develop their own software. This is not for every DSO the case since other DSOs rely on external consulting companies for software development. However, according to the interviewee, to ensure a safe implementation of a Digital Twin, there needs to be a balance between in-house knowledge and specialised external support.

### Interviewee 9

#### Background

Interviewee 9 is a Digital Twin expert and is a PhD candidate working on Digital Twins for electricity networks. This interviewee has a background in Mechanical Engineering and Sustainable Energy Technology.

#### Summary

Interviewee 9 explains that a Digital Twin is a software platform that includes all models and tools used for day-to-day operations and future planning of the electricity grid, including real-time data, state estimation, control methods testing and scenario analysis. In this way, a Digital Twin can provide a complete overview of the electricity grid.

According to interviewee 9, ensuring data quality, validation and cybersecurity are important to the implementation of Digital Twins. A Digital Twin must be able to handle different data sources, process the data, and maintain real-time updates. Interviewee 9 explains that the development of a Digital Twin is more a software challenge than an electrical engineering one since it requires collaboration with computer scientists to manage and integrate data. The interviewee states that visualisation tools are needed to make data and control options understandable for operators in the control room, and to avoid ambiguities regarding the interpret of the model.

Interviewee 9 believes that Digital Twins should not replace human operators but support them by validating control methods and providing insights. Additionally, the interviewee believes that collaboration among DSOs can contribute to improve system safety by sharing data and developing standardised approaches to be able to manage an interconnected network. However, this could be a challenge due to privacy issues. It is therefore important to decide who owns, maintains, and updates the Digital Twin. Furthermore, open-source frameworks could encourage standardisation and data sharing, which could improve the performance of the Digital Twin.

## Appendix E: Original STPA-Structure

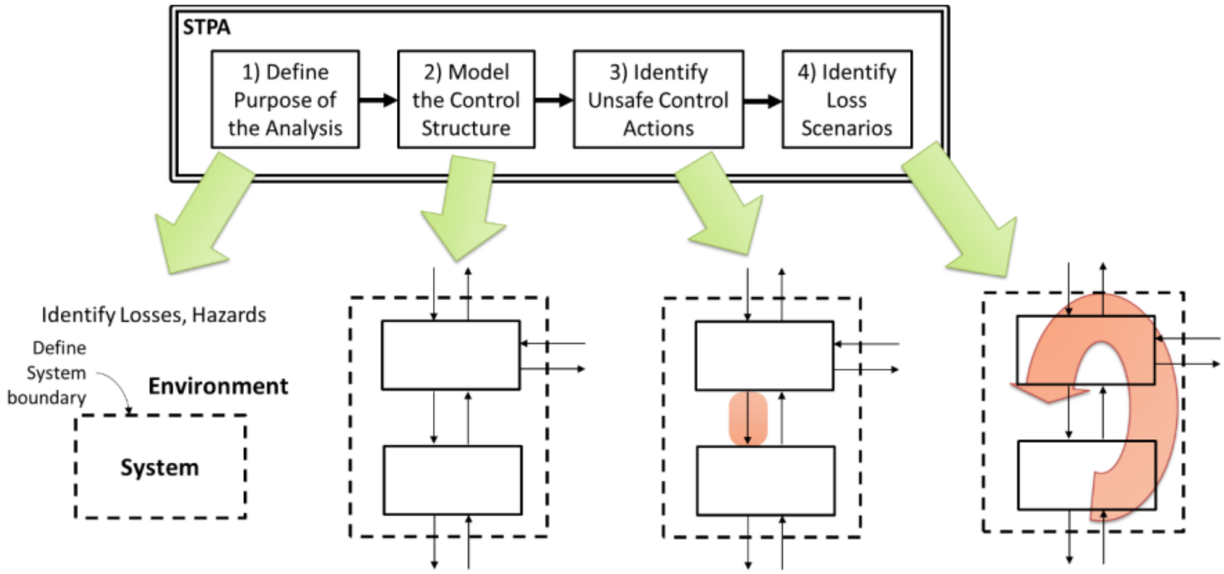


*Figure 10: Structure of original System-Theoretic Process Analysis (STPA) from Leveson and Thomas (2018)*

## Appendix F: Losses that result from loss scenarios and hazards

*Table 17: Losses that result from loss scenarios and system-level hazards*

| **Loss scenarios** | **System-level hazard** | Losses |
|---|---|---|
| LS-12 | H-1: Unauthorised access to sensitive data by external third parties | L-3, L-6 |
| LS-11 &12 | H-2: Digital Twin not complying to identified industry protocols, safety laws and regulations | L-1, L-2, L-4, L-5, L-6 |
| LS 1 – 6, 10, 13 & 16 | H-3: Inaccurate Digital Twin models | L-1, L-2, L-4, L-5 |
| LS-4, 8 & 16 | H-4: Ambiguous Digital Twin representations | L-1, L-2, L-4, L-5 |
| LS-9, 14 & 15 | H-5: Overly complex Digital Twin models | L-1, L-2, L-4, L-5 |
| LS-7 | H-6: Digital Twin failure caused by lack of computational power | L-1, L-2, L-4, L-5 |

# Appendix G: The constraints that mitigate or prevent loss scenarios

## 1. Technical constraints

**Input data**

LS-1: Input data quality of Digital Twin is poor

- C-1.1: Perform data quality validation checks

LS-2: There is a lack of measurements

- C-2.1: Provide alerts when there is insufficient measurement data

LS-3: There is insufficient data for acceptable model performance of Digital Twin

- C-3.1: Implement strategies to generate sufficient data
- C-3.2: Automated actions taken by Digital Twins must be validated and monitored by human controller

LS-4: There is a lack of data standardisation and/or categorisation for Digital Twin input data

- C-4.1: Establish clear data taxonomy and data standards
- C-4.2: Categorise and standardise data before using it as input for the Digital Twin

**Systems**

LS-5: The systems integrated in the Digital Twin are not easily interoperable

- C-5.1: Establish collaborative objectives aimed at system integration between different relevant departments
- C-5.2: Provide middleware and translation layers to facilitate system integration

**Model complexity**

LS-6: The model only accounts for a limited portion of conditions

- C-6.1: Test the Digital Twin model on different conditions

LS-7: Handling large volumes of data can cause computational overload

- C-7.1: Optimise algorithms within Digital Twin to handle large volumes of data
- C-7.2: Establish data strategies for occasions of large volumes of input data

LS-8: The visualisations of the Digital Twin are unclear

- C-8.1: Test visualisations on interpretability on all departments and stakeholders working with the Digital Twin

LS-9: More input variables are used than necessary

- C-9.1: Establish clear performance objectives of the Digital Twin
- C-9.2: Perform sensitivity analysis to choose most important variables

LS-10: The accuracy of the Digital Twin's models or algorithms is considerably low

- C-10.1: Set constraints on the minimal accuracy of the models
- C-10.2: Test models on accuracy

## 2. Institutional constraints

LS-11: The required safety and communication protocols and regulations of the Digital Twin are not clear to everyone involved in the Digital Twin development process

- C-11.1: Provide everyone involved in the Digital Twin development process with trainings on safety and communication protocols and regulations

LS-12: Confidential data is not handled carefully

- C-12.1: Provide everyone involved in the development process and operation of the Digital Twin with trainings on data confidentiality
- C-12.2: Let everyone involved in the development process and operation of the Digital Twin sign confidentiality agreements
-

LS-13: The DSO lacks adequate data governance

- C-13.1: Establish clear data governance regulations within the DSO
- C-13.2: Establish a data governance department within the DSO

## 3. Process constraints

**Development**

LS- 14: The Digital Twin development team does not use a structured development approach

- C-14.1: Document a structured Digital Twin development approach
- C-14.2: Establish regulations and guidelines for teams/departments to adhere to the structured Digital Twin development approach

**Collaboration**

LS-15: There is a lack of internal technical expertise

- C-15.1: Use a digital thread to design, evaluate and manage the Digital Twin collaboratively with IT firms
- C-15.2: Hire Digital Twin experts to gain knowledge in-house
- C-15.3: Use consultants to bridge the knowledge gap between DSOs and IT firms

LS-16: Departments are hesitant to collaborate on the implementation and operation of Digital Twins

- C-16.1: Establish collaboration guidelines

# Appendix H: Complete overview of constraints, loss scenarios, unsafe control actions, system-level hazards and losses

*Table 18: Complete overview of constraints with corresponding loss scenarios, unsafe control actions, system-level hazards and losses*

| Constraint (C) | Loss Scenario (LS) | Unsafe Control Action (UCA) | System-Level Hazard (H) | Losses (L) |
|---|---|---|---|---|
| **C-1.1: Perform data quality validation checks** | **LS-1:** Input data quality of Digital Twin is poor | **UCA-1.1:** Using the low-quality data in the Digital Twin without validation | **H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-2.1: Provide alerts when there is insufficient measurement data** | **LS-2:** There is a lack of measurements | **UCA-2.1:** Not enough sensors have been installed to capture necessary measurements | **H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-3.1: Implement strategies to generate sufficient data** | **LS-3:** There is insufficient data for acceptable model performance of Digital Twin | **UCA-3.1:** Developing a Digital Twin despite the data insufficiencies | **H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-3.2: Automated actions taken by Digital Twins must be validated and monitored by human controller** | **LS-3:** There is insufficient data for acceptable model performance of Digital Twin | **UCA-3.1:** Developing a Digital Twin despite the data insufficiencies | **H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-4.1: Establish clear data taxonomy and data standards** | **LS-4:** There is a lack of data standardisation and/or categorisation for | **UCA-4.1:** Using unstandardised and uncategorised datasets as input for the Digital Twin | **H-3:** Inaccurate Digital Twin models<br>**H-4:** Ambiguous | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss |

| | | | | |
|---|---|---|---|---|
| | Digital Twin input data | | Digital Twin representations | **L-5:** Loss of electrical power network reliability |
| **C-4.2: Categorise and standardise data before using it as input for the Digital Twin** | **LS-4:** There is a lack of data standardisation and/or categorisation for Digital Twin input data | **UCA-4.1:** Using unstandardised and uncategorised datasets as input for the Digital Twin | **H-3:** Inaccurate Digital Twin models<br>**H-4:** Ambiguous Digital Twin representations | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-5.1: Provide middleware and translation layers to facilitate system integration** | **LS-5:** The systems integrated in the Digital Twin are not easily interoperable | **UCA-5.1:** The integration of systems without ensuring compatibility | **H-3: Inaccurate Digital Twin models** | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-6.1: Test the Digital Twin model on different conditions** | **LS-6:** The model only accounts for a limited portion of conditions | **UCA-6.1:** Developing a Digital Twin model that ignores occurring conditions | **H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-7.1: Optimise algorithms within Digital Twin to handle large volumes of data** | **LS-7:** Handling large volumes of data can cause computational overload | **UCA-7.1:** Feeding large volumes of data into the Digital Twin leading to computational overload | **H-6:** Digital Twin failure caused by lack of computational power | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-7.2: Establish data strategies for occasions of large volumes of input data** | **LS-7:** Handling large volumes of data can cause computational overload | **UCA-7.1:** Feeding large volumes of data into the Digital Twin leading to computational overload | **H-6:** Digital Twin failure caused by lack of computational power | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |

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| **C-8.1: Test visualisations on interpretability on all departments and stakeholders working with the Digital Twin** | **LS-8:** The visualisations of the Digital Twin are unclear | **UCA-8.1:** Using complex visualisations that are not interpretable by everyone using the Digital Twins | **H-4:** Ambiguous Digital Twin representations | **L-1:** Loss of life or injury to field workers **L-2:** Damage to electrical infrastructure **L-4:** Financial loss **L-5:** Loss of electrical power network reliability |
| **C-9.1: Establish clear performance objectives of the Digital Twin** | **LS-9:** More input variables are used than necessary | **UCA-9.1:** Including more variables than necessary in the model without enhancing the accuracy of the Digital Twin | **H-5:** Overly complex Digital Twin models that are difficult to manage and understand | **L-1:** Loss of life or injury to field workers **L-2:** Damage to electrical infrastructure **L-4:** Financial loss **L-5:** Loss of electrical power network reliability |
| **C-9.2: Perform sensitivity analysis to choose most important variables** | **LS-9:** More input variables are used than necessary | **UCA-9.1:** Including more variables than necessary in the model without enhancing the accuracy of the Digital Twin | **H-5:** Overly complex Digital Twin models that are difficult to manage and understand | **L-1:** Loss of life or injury to field workers **L-2:** Damage to electrical infrastructure **L-4:** Financial loss **L-5:** Loss of electrical power network reliability |
| **C-10.1: Set constraints on the minimal accuracy of the models** | **LS-10:** The accuracy of the Digital Twin's models or algorithms is considerably low | **UCA-10.1:** Using Digital Twins without validating and testing the algorithms on accuracy | **H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers **L-2:** Damage to electrical infrastructure **L-4:** Financial loss **L-5:** Loss of electrical power network reliability |
| **C-10.2: Test models on accuracy** | **LS-10:** The accuracy of the Digital Twin's models or algorithms is considerably low | **UCA-10.1:** Using Digital Twins without validating and testing the algorithms on accuracy | **H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers **L-2:** Damage to electrical infrastructure **L-4:** Financial loss **L-5:** Loss of electrical power network reliability |
| **C-11.1: Provide everyone involved in the Digital Twin development** | **LS-11:** The required safety and communication | **UCA-11.1:** Not providing everyone involved in the development | **H-2:** Digital Twin not complying with identified industry | **L-1:** Loss of life or injury to field workers **L-2:** Damage to electrical infrastructure |

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| **process with training on safety and communication protocols and regulations** | protocols and regulations of the Digital Twin are not clear to everyone involved in the development process | process of the Digital Twin with information on safety and communication protocols and regulations | protocols, safety laws, and regulations | **L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability<br>**L-6:** Loss of reputation |
| **C-12.1: Provide everyone involved in the development process and operation of the Digital Twin with training on data confidentiality** | **LS-12:** Confidential data is not handled carefully | **UCA-12.1:** Allowing unauthorised access to confidential data | **H-1:** Unauthorised access to sensitive data by external third parties | **L-3:** Loss of data privacy<br>**L-6:** Loss of reputation |
| **C-13.1: Establish clear data governance regulations within the DSO** | **LS-13:** The DSO lacks adequate data governance | **UCA-13.1:** Not establishing clear data governance regulations within the DSO | **H-2:** Digital Twin not complying with identified industry protocols, safety laws, and regulations<br>**H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability<br>**L-6:** Loss of reputation |
| **C-13.2: Establish a data governance department within the DSO** | **LS-13:** The DSO lacks adequate data governance | **UCA-13.1:** Not establishing clear data governance regulations within the DSO | **H-2:** Digital Twin not complying with identified industry protocols, safety laws, and regulations<br>**H-3:** Inaccurate Digital Twin models | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability<br>**L-6:** Loss of reputation |
| **C-14.1: Document a structured Digital Twin development approach** | **LS-14:** The Digital Twin development team does not use a structured development approach | **UCA-14.1:** Not having the preconditions of the Digital Twin clearly mapped out<br>**UCA-14.2:** Using redundant variables that do not improve | **H-5:** Overly complex Digital Twin models that are difficult to manage and understand | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |

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| | | the performance of the Digital Twin<br>**UCA-14.3:** Not having the purpose of the Digital Twin clear before the development of the Digital Twin | | |
| **C-14.2: Establish regulations and guidelines for teams/departments to adhere to the structured Digital Twin development approach** | **LS-14:** The Digital Twin development team does not use a structured development approach | **UCA-14.1:** Not having the preconditions of the Digital Twin clearly mapped out<br>**UCA-14.2:** Using redundant variables that do not improve the performance of the Digital Twin<br>**UCA-14.3:** Not having the purpose of the Digital Twin clear before the development of the Digital Twin | **H-5:** Overly complex Digital Twin models that are difficult to manage and understand | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-15.1: Use a digital thread to design, evaluate, and manage the Digital Twin collaboratively with IT firms** | **LS-15:** There is a lack of internal technical expertise | **UCA-15.1:** Outsourcing development without internal oversight | **H-5:** Overly complex Digital Twin models that are difficult to manage and understand | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-15.2: Hire Digital Twin experts to gain knowledge in-house** | **LS-15:** There is a lack of internal technical expertise | **UCA-15.1:** Outsourcing development without internal oversight | **H-5:** Overly complex Digital Twin models that are difficult to manage and understand | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-15.3: Use consultants to bridge the knowledge gap** | **LS-15:** There is a lack of internal technical expertise | **UCA-15.1:** Outsourcing development | **H-5:** Overly complex Digital Twin models that are difficult to | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure |

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| **between DSOs and IT firms** | | without internal oversight | manage and understand | **L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |
| **C-16.1: Establish collaborative objectives aimed at system integration between different relevant departments** | **LS-16:** Departments are hesitant to collaborate on the implementation and operation of Digital Twins | **UCA-16.1:** Departments/teams work siloed | **H-3:** Inaccurate Digital Twin models<br>**H-4:** Ambiguous Digital Twin representations | **L-1:** Loss of life or injury to field workers<br>**L-2:** Damage to electrical infrastructure<br>**L-4:** Financial loss<br>**L-5:** Loss of electrical power network reliability |