Developing a Framework for the Application of Parametric Design Thinking in Infrastructure Engineering: A Case Study of the Dike Reinforcement Design Process

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ABSTRACT:
Parametric Design Thinking (PDT) is a broadly defined design method based on a digital scripting environment with the purpose of quickly altering design alternatives. PDT includes various application types with different functionalities; in this research defined as PDT classes. As the application of PDT is new within infrastructure engineering, there is no consensus yet on the definition of PDT classes in this field. Therefore, a strategic application of PDT in infrastructure projects such as dike reinforcements is difficult. As a basis for the strategic application of PDT in infrastructure engineering, this research proposes a framework for the alignment of PDT classes with application factors (benefits and enablers) and the design process. The framework has the purpose of (1) determining the application areas of PDT classes in the design process, and (2) identifying the main factors on which the application of PDT is dependent. It is found that PDT within infrastructure engineering can be classified in three intersecting research fields: models of engineering knowledge, models of design, and process models of digital design. Via the identification of specific variables with functionalities, these three research fields can be specified in PDT classes and analysed in the context of a specific design process. The developed framework is demonstrated in two case studies at a contractor for dike reinforcements. Results show several transformations of application areas accompanied by specific factors determining these transformations. Based on the framework results, recommendations are provided for increasing PDT application within dike reinforcement projects. By analysing the dike reinforcement design process as a case study, this research suggests that the proposed framework setup and procedure could be used to scope the application of PDT in infrastructure engineering projects and could act as a basis for the application of PDT within this domain.

1. INTRODUCTION

1.1. Background and motivation

There has been a growing practical need for the design of dike reinforcements in the Netherlands, as the Intergovernmental Panel on Climate Change states that the global mean level of seas and rivers will most likely rise between 0.29m and 1.1m by the end of this century (IPCC, 2019). In response to this, public bodies such as Rijkswaterstaat and Water Boards are committed to improving the performance of the dikes and other water defence systems. In the National Flood Defence Program (Dutch: *HoogWaterBeschermingsProgramma*) is stated that 1.300 km of dikes need to be reinforced in 30 years (Rijkswaterstaat, 2020). The type of contract for these projects has changed from construct only to design and construct. This implies contractors take a larger responsibility in the design than in previous projects. Even though contractors are already working on multiple large scale construction projects, it will be difficult to reach the set goal at the current pace of design and construction (De Ingenieur, 2016). One of many factors preventing the fulfilment of the goal is the issue that each design cycle tends to take a lot of time. This is caused by (i) the complexity of design calculations, (ii) the low allowable failure chance, (iii) the many interfaces with the environment, and (iv) the need for a high level of detail in an early design phase (Boskalis, 2021). Also, long discussions with stakeholders lead to many design cycles typically continuing far into the construction phase. Therefore, the design process of dike reinforcement for contractors needs to be scrutinised. Parametric Design Thinking (PDT), as defined in the next paragraph, could be a solution to simplify and shorten the design process since it has already been demonstrated in infrastructure engineering (Barazzetti & Banfi, 2017; Vilgertshofer & Borrmann, 2017). Dike reinforcements can be classified as infrastructure projects since the dike reinforcement design process has similar characteristics to other types of infrastructure, i.e., a mesh network of assets, longitudinal structures connecting point structures and a focus on non-graphical data (Bradley et al., 2016). Its large number of design cycles and the need for both high flexibility and level of detail in an early design phase correspond to the characteristics of a PDT-based design process (Harding & Shepherd, 2017).

In the context of this article, PDT is defined as a design methodology based on a digital scripting environment with the purpose of quickly altering design alternatives (Oxman & Gu, 2015). PDT is often referred to with the term parametric designing or generative designing (Woodbury, 2006; Jabi, 2013; Abrishami et al., 2014). Besides, several other related terms to PDT can be identified, such as: BIM-based designing and GIS-based designing (Bradly et al., 2016; Barazzetti & Banfi, 2017). In between these terms, there are certain differences and similarities. Both BIM and GIS are systems to manage construction-related data (Bradley et al., 2016). While GIS has a greater focus on non-graphical and geospatial data than BIM, the latter offers more detailed visualisations and has the ability to organise data related to objects (Barazzetti & Banfi, 2017). Comparing BIM and GIS to parametric design and generative design, the biggest difference relates to the focus on multi-operation iteration and dataflow modelling for the latter two (Biljecki et al., 2019). While a parametric design allows the designer to make changes on parameters that trigger design iterations via workflows, a generative design automates part of the decision-making process of the designer by using algorithms (Abrishami et al., 2014). In this study, the definition of PDT incorporates aspects of all aforementioned related terms. Oxman (2017) defines three intersecting research fields that form the research domain of PDT: *models of engineering knowledge*, *models of design*, and *process models of digital design*, as visualised in Figure 1. Each of these fields can be used to classify PDT into various application types with different functionalities; in this research defined as PDT classes.

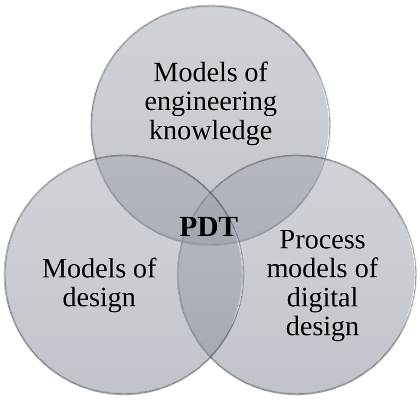


Figure 1: Diagram of intersecting fields of research in Parametric Design Thinking

Since PDT is not yet generally applied, there is a need to further explore the concept and to develop and formulate new disciplinary knowledge in order to make the transition towards the general application of PDT (Oxman, 2017). PDT is already explored in architectural engineering and structural engineering, however, opportunities exist for the domain of infrastructure engineering (Bradley et al., 2016). More specifically, Bradley et al. (2016) state a need for strategical alignment of digital design methodologies like PDT with design processes of contractors in the infrastructure engineering domain. In infrastructure engineering, there is no consensus yet on defining different PDT classes, their application areas (scoping where in the design process PDT is or could be applicable) and their application factors (i.e., benefits and enablers associated with the application). Therefore, strategic application of PDT in specific infrastructure projects is difficult. In this paper, the scientific perspective of Oxman (2017) is adopted as a basis for further exploration of PDT in the field of infrastructure engineering.

1.2. Research objective and scope

The objective of this research is to develop a framework facilitating a strategic application of PDT in specific infrastructure engineering projects. The framework has the purpose of (1) determining the application areas of PDT classes in the design process, and (2) identifying the main factors on which the application of PDT is dependent. Two dike reinforcement projects are used as a case study in order to develop the framework for this specific type of infrastructure projects. The case studies include the knowledge areas of modelling, cost-, and geotechnical engineering, as these are the main expert domains for the design of dike reinforcements (Boskalis, 2021). In this way, the study aims to determine the application areas and factors related to the application of PDT in the dike reinforcement design process.

1.3. Reading guide

The paper is structured as follows: first, in section 2, the methodology of the research is presented. After that, in section 3, the framework setup for the infrastructure engineering domain is created based on a literature review. Section 4 elaborates on the development of the framework for the dike reinforcement case studies. Finally, in sections 5 and 6, the results are discussed and conclusions on the application of PDT for dike reinforcements as well as the general use of the framework are given.

2. METHODOLOGY

This section describes first the research questions and related conceptual framework. This conceptual framework forms the basis for the to be created framework in this research. After that, the research design is discussed.

2.1. Conceptual framework

In order to fulfil the research objective, four research questions need to be answered. In Figure 2, a four-component conceptual framework is proposed which combines the research questions of this study. The research questions and corresponding framework components are:

1. How can PDT be classified for application in infrastructure engineering? *The PDT typology*; classifying PDT according to common features, answers the first research question.
2. What are the main factors on which the application of PDT in infrastructure engineering is dependent? *Application factors*; defining the factors which determine the benefits and enablers of PDT classes, answers the second research question.
3. How can the design process be classified for the application of PDT? *The design process*; defining the design phases and their corresponding design loops, answers the third research question.
4. What is the relation between the PDT typology, application factors and the design process? *The fit between the PDT typology, factors and the design process*; specifying the application areas, answers the fourth research question.

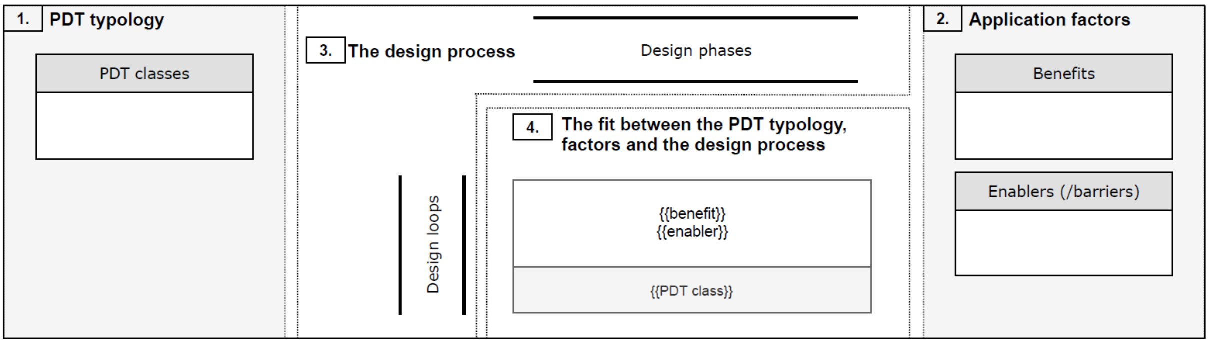


Figure 2: The four-component conceptual framework

The content of each component of the framework is detailed in Sections 3 & 4. The *PDT typology* and *Application factors* are formulated from a literature review and considered as the 'framework setup'. The remaining components need to be specified for a specific infrastructure project via case studies. For *The design process*, each identified design phase or loop is represented by respectively a single column or row, drafting a matrix within this framework component. The component *The fit between the PDT typology, factors and the design process* – hereafter referred to as *The fit* – visualises the relationship between the first three components by scoping application areas within the design phases and design loops, and specifying the PDT class, benefits and enablers for these application areas. In this article, *The fit* specifies the currently applied PDT classes, preferred PDT classes, and the benefits and enablers which apply to the transformation towards this preferred situation.

2.2. Research design

In order to develop the *PDT typology* (RQ 1) and *Application factors* (RQ 2), a literature review is conducted. A total of 40 articles relevant for this research from journals with an impact factor higher than 1.0 are reviewed. Besides, examples are obtained regarding practical applications and PDT systems in infrastructure engineering. A PDT system is in this research defined as a design tool or software based on the design methodology of PDT.

The limited theoretical basis regarding the application of PDT in dike reinforcements demanded an empirical and qualitative research approach for the development of framework components *The design process* (RQ 3) and *The fit* (RQ 4). The research follows Baskarada's (2014) qualitative case study guideline, which is based on the universally accepted six-stage case study by Yin (1994). Figure 3 shows the research design for the case studies, consisting of the six steps related to the guideline; i.e. plan, prepare, collect, analyse, design and share (Baskarada, 2014).

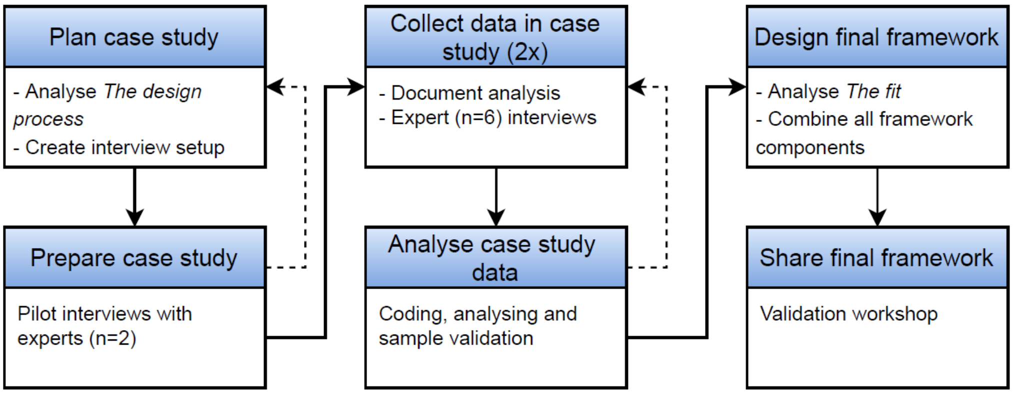


Figure 3: Research design for the case studies

The following two case study dike reinforcement projects are analysed:

<u>Case 1 'Markermeerdijken':</u> a Dutch dike reinforcement project which is carried out by an alliance between several contractors and engineering firms. In total, a 33 km dike needs to be reinforced. The project was put on the market in 2014 and is currently near the end of its construction phase. Within

this project, a contract form of early contractor involvement was used by the client. Only a few parametric systems are applied during the design process of this project (HHNK, 2021).

Case 2 'IJsselwerken': a Dutch dike reinforcement project which is carried out by a single contractor and engineering firm. In total, almost 30 km dike needs to be reinforced. The project was put on the market in 2020 and is currently in its design phase. Within this project, a contract form of early contractor involvement was used by the client. Initiatives are taken to apply parametric systems during the design process of this project (Boskalis, 2021).

Primarily, *The design process* is analysed by document studies on corporate standards and design guidelines from the case studies. Besides, interviews with two design modellers, two cost- and two geo-engineers for both case studies are conducted. A total sample size of twelve in a single market or relatively homogeneous population has been accepted as a valid sample size for theoretical saturation in qualitative research (Boddy, 2016). Saturation is reached when new rounds of data collection confirm prior findings and yield almost no new findings. The design process is documented by the creation of a Business Process Model and Notation (BPMN) by the standard of Chinosi & Trombetta (2012). BPMN is a method of illustrating design processes in the form of a diagram similar to a flowchart, in which design loops can be made easily visible.

In order to study *The fit*, an interview setup is prepared using the examples of practical applications and PDT systems (see Appendix A). The interview setup is tested during two pilot interviews. In total, four modellers, four geo-engineers, and four cost-engineers participated in semi-structured in-depth interviews. Semi-structured interviews are favoured as they allow investigation of individuals' thoughts and perceptions on the subject (Baskarada, 2014). Credibility of the data is enhanced through triangulation and cross-validation between the participants (Verschuren & Doornewaard, 2007). For the analysis of the currently applied PDT, a within-case analysis and a cross-case analysis is carried out. For the analysis on the preferred application of PDT, the participants had difficulties with separating the case study from their earlier executed projects. Therefore, the data resulting from the two cases are combined. The in-depth interviews are transcribed and coded following several coding rounds in Atlas.ti, version 9.0 (Atlas.ti, 2021). First, codes are created for the PDT typology and elements of the design process. Secondly, the codes further specified the application factors (benefits and enablers). Finally, all framework components are combined in order to create the final framework.

Construct validity is endorsed by expert validation as well as a validation workshop. Expert validation is done with two interdisciplinary experts in infrastructure engineering familiar with PDT. These experts reflected on the development and the results of each framework component. During the validation workshop, a multi-disciplinary team of case study participants tried to gain further insights into the application of PDT using the framework results.

3. DEVELOPING THE FRAMEWORK SETUP

This section contains the development of the first two components of the framework, referred to as the framework setup. First, the PDT typology is developed via a literature review. Second, literature is reviewed regarding the factors (benefits and enablers) on which the application of PDT is dependent. The final section combines this knowledge in order to fill the first two components of the framework.

3.1. Development of the PDT typology

A typology classifies a phenomenon of a domain under study into classes according to common features (Croft, 2002). For the PDT typology, three main dimensions are proposed of which the intersection of its variables can be altered to describe a specific PDT class. These dimensions are, *model of engineering knowledge*, *model of design*, and *process model of digital design*. The dimensions are in line with the intersecting fields of research in PDT as explained by Oxman (2017) (see Figure 1). For each dimension, several variables are proposed. All dimensions and variables (e.g., object-oriented, procedural) are explained in the following subsections. Figure 4 visualises the three dimensions of the PDT typology and their variables.

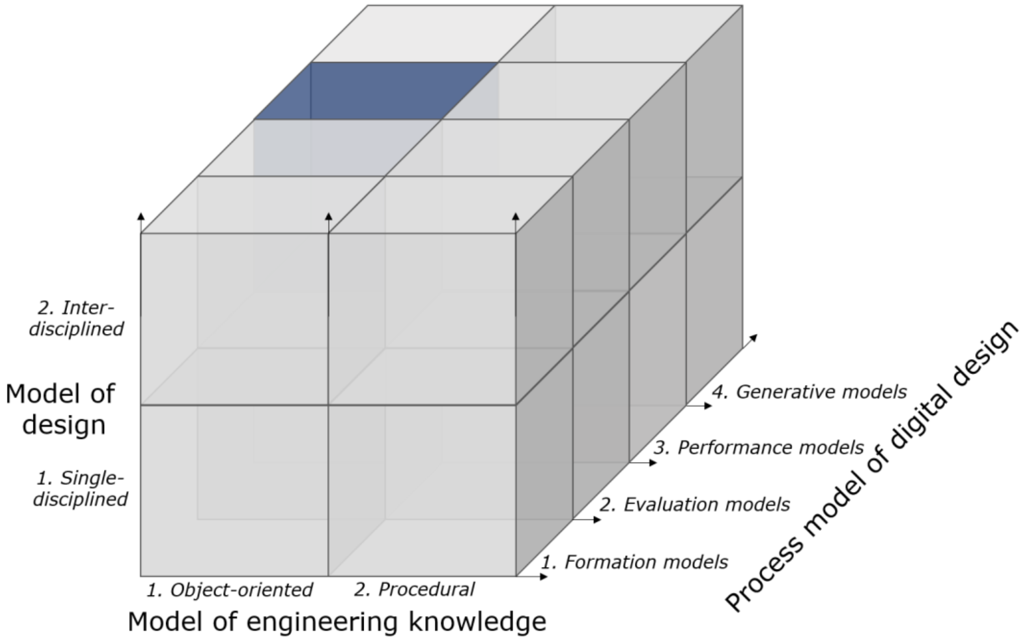


Figure 4: Visualisation of PDT typology, PDT class [1,2,3] highlighted blue

A PDT class can be described by their unique combination of variables, using the numbers of the variables according to the notation:

$$PDT\ class\ [x, y, z]$$

x = model of engineering knowledge
y = model of design
z = process model of digital design

It should be stated that PDT classes are not mutually exclusive, meaning that a single PDT system is not limited to a single PDT class. The arrows within the figure indicate the direction for moving towards technological advanced PDT classes. The blue marked cube in this figure, PDT class [1,2,3], is an example of a specific PDT class that is composed of the variables; object-oriented, interdisciplinary, and performance models.

3.1.1. Model of engineering knowledge

Models of engineering knowledge can be considered a rule-based representation of objects and/or procedures that together define a design (Oxman, 2017). For the model of engineering knowledge dimension, two variables are proposed; object-oriented models and procedural models (Shah & Mäntylä, 1995; Borrmann et al., 2012; Harding et al., 2012). *Object-oriented* models are defined as digital design models using a system of interacting objects as a way to capture relations in a design (Shah & Mäntylä, 1995; Abbondati et al., 2020). Object-oriented models store knowledge in the outcome of the design process, while *procedural* models store the history of the individual design operations. Procedural models use sets of rules and functions to model a design (Borrman et al., 2012).

Example: procedural model
Within Autodesk Dynamo, design workflows can be specified in which the history of the design operations is saved. In this way, first the procedures of the design are defined. Second, by changing values within the procedures, different design elements are created (Autodesk, 2021).

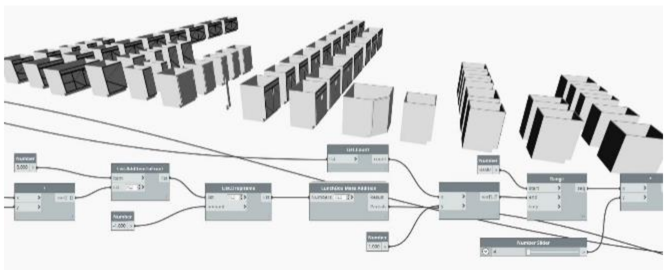


Figure 5 (a) illustrates how in an object oriented model, a dike section geometry is the unique outcome of a linear design process; any implicit decisions taken along the design are not stored. Engineering knowledge is for example captured in 3D model elements, attributes, volumes and quantities. A procedural model, see Figure 5 (b), relies instead on connected algorithms to perform design operations like inputting data, generating a terrain model, and calculating volumes and quantities. In this type of modelling, first the procedures are defined, and then the design elements are created. This facilitates a non-linear design process, in which the history of individual design operations is stored (Vilgertshofer & Borrmann, 2017; Biancardo et al., 2020).

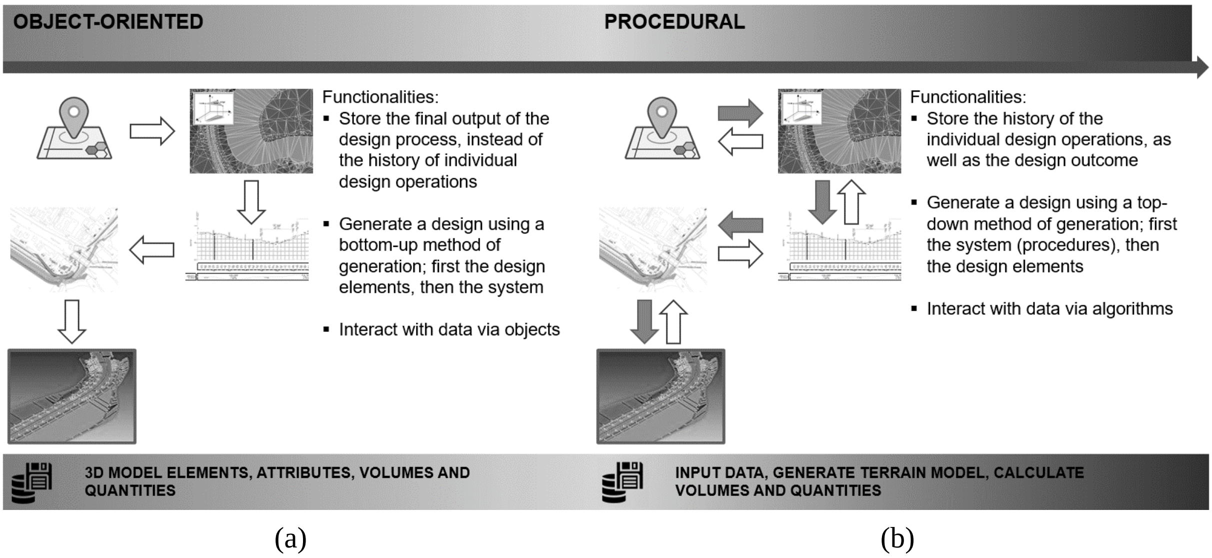


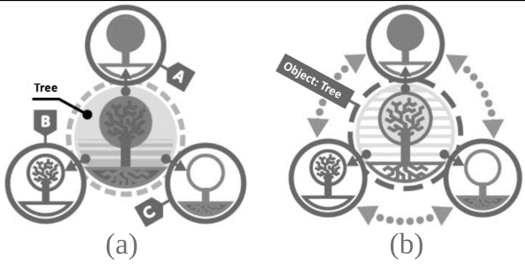
Figure 5: The difference between object-oriented (a) and procedural (b) models with an example for a dike section

3.1.2. Model of design

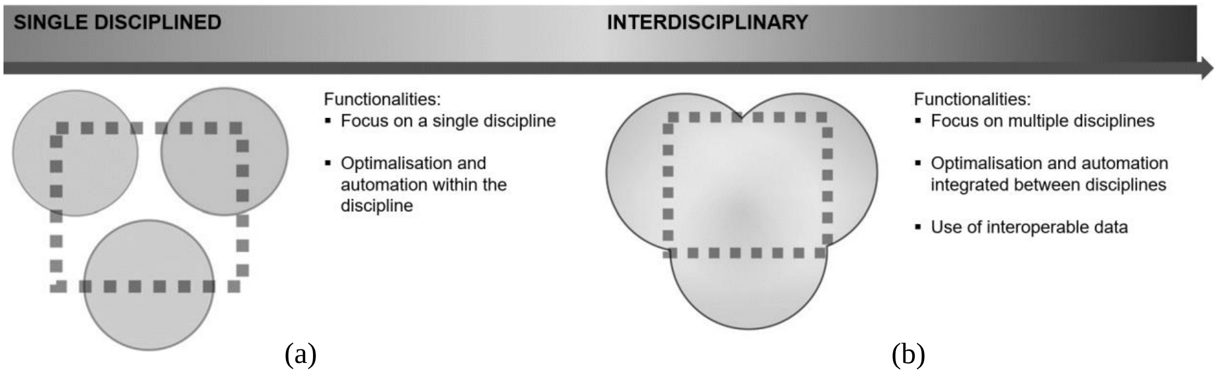
The second dimension of the PDT typology refers to the research field regarding the integration of data, which defines the input for the generation of a design (Oxman, 2017). The more design disciplines involved in a PDT system, the more complex the model of design, resulting in a different design approach (Haymaker et al., 2018; Emami, 2019). For the model of design dimension, two variables are proposed, i.e., a *single-disciplined* and an *interdisciplinary* model.

Example: interdisciplinary model

Different disciplines are modelling an object, in which object codes and names are not specified per discipline individually (a), but are integrally determined (b). In an interdisciplinary model, interoperable data provides an unambiguous interpretation of the same object by different disciplines (Berghout, 2018).



As visualised in Figure 6 below, the difference mainly lies in the interoperability of data used within a PDT system. When multiple disciplines are incorporated in a single system, different data should be combined, whereby each discipline usually uses its own format (even if it concerns the same objects). Especially for the infrastructure engineering domain, research by Barazzetti & Banfi (2017) and Zhang et al. (2018) state that incorporating geotechnical design information within interdisciplinary PDT brings additional challenges, as geo-engineers use a different data format than geometrical modellers. Furthermore, research of Smith (2014) examined this issue associated with the integration of cost aspects in the design model. Also for this discipline, different data formats are often used in comparison to the formats in the geometrical model. Research suggests that the more disciplines integrated within PDT, the more complex the creation of a PDT system (Haymaker et al., 2018; Emami, 2019).



(a) (b)

Figure 6: The difference between single disciplined (a) and interdisciplinary (b) models

3.1.3. Process model of digital design

This third dimension of the PDT typology refers to the different process models of digital design. These models represent information flows and embedded logic regarding the interaction between a designer and a PDT system (Oxman, 2006). Oxman (2006) provides a generic formulation to represent process models of digital design, see Figure 7. Within this model, different interactions between a designer (D), and digital design processes of representation (R), evaluation (E), performance (P), and generation (G) can be defined. Also, distinction is possible between implicit or explicit flows of digital information, and whether designer interaction takes place.

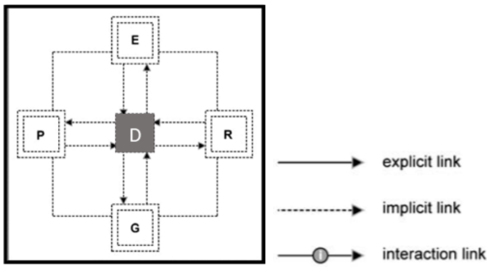


Figure 7: Generic formulation of process models of digital design (Oxman, 2006)

As an example, the process model of digital design of a non-parametric, traditional CAD system is given in Figure 8 (a). Traditional CAD systems are characterized mainly as being descriptive through manipulating the graphical representation of digital objects. Information flows with evaluation, performance or generation is only implicitly done via the designer. Using the generic formulation of Oxman (2006), distinctions can be made between several process models of digital design within the PDT typology, i.e., formation models, evaluation models, performance models and generative models (Oxman, 2017) (Figure 8 (b-e)). For the process model of digital design dimension, these four models are proposed as variables.

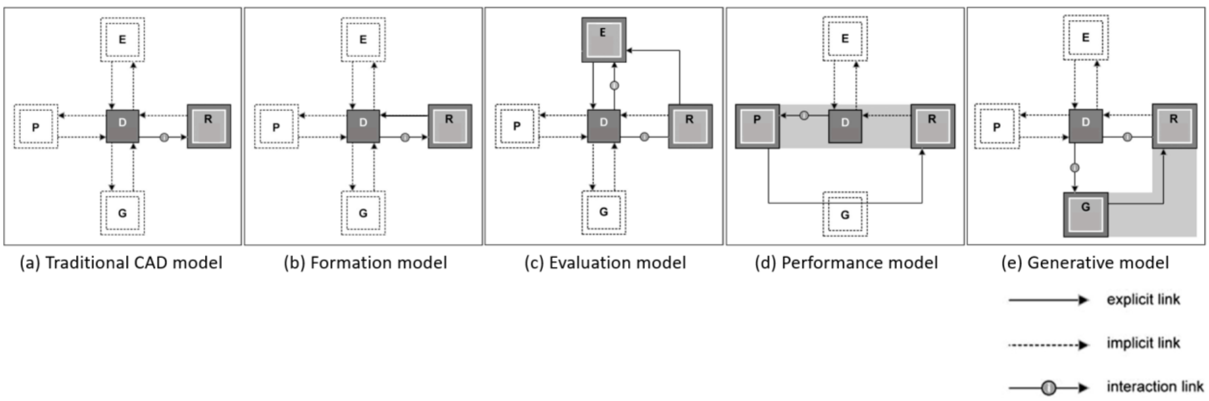


Figure 8: Generic formulation of process models of digital design for a traditional CAD model (a) and its four variables of the PDT typology (b-e)

The differences between the four variables are illustrated in Figure 9. *Formation models* are traditional digital design models, where the formation of geometries is parametrised and partly automated (Oxman, 2006). An example of software facilitating formation models is the Subassembly Composer software from Autodesk (Autodesk, 2020). Within literature, Raza et al. (2017) used a formation model in order to analyse the flexibility of a parametric earthwork model for road projects. *Evaluation models* directly link representation with evaluation and give the designer the possibility to interact with this evaluation (Oxman, 2006). Numerical modelling software like Plaxis from Bentley would typically fall into this category (Bentley, 2021). Examples of this type of PDT in literature are given by Vilgertshofer & Borrmann (2017), who researched automatic detailing in tunnel engineering, and Krantz et al. (2015), who conducted automated energy analysis on the design of the superstructure of a bridge. *Performance models* can be regarded as such when formation models are driven by a desired performance and the designer interacts only with the design by altering this performance (Oxman, 2006). Examples of software facilitating this kind of modelling are Dynamo, Grasshopper Rhino or the VIKTOR platform (Autodesk, 2021; Rhino, 2021, VIKTOR, 2021). Within literature, Biancardo et al. (2020) stated that the use of a performance models in their case study of a roadway resulted in the ability to quickly create multiple combinations of the design representation. *Generative models* are characterised by the provision of algorithms for the design generation process. The model can generate multiple solutions in parallel within the provided boundary conditions, and the designer is interacting with these generative algorithms via goals and constraints (Oxman, 2006). Software like the recently released Project Refinery from Autodesk typically falls into this category (Autodesk, 2021). Examples of this type of modelling in literature are illustrated by Georgoula & Vilgertshofer (2018), who created a generative design system that automatically designed alternatives for bridge abutments after defining its alignments, and Nagy et al. (2018), who designed neighbourhood layouts by algorithms that integrated financial and energy goals.

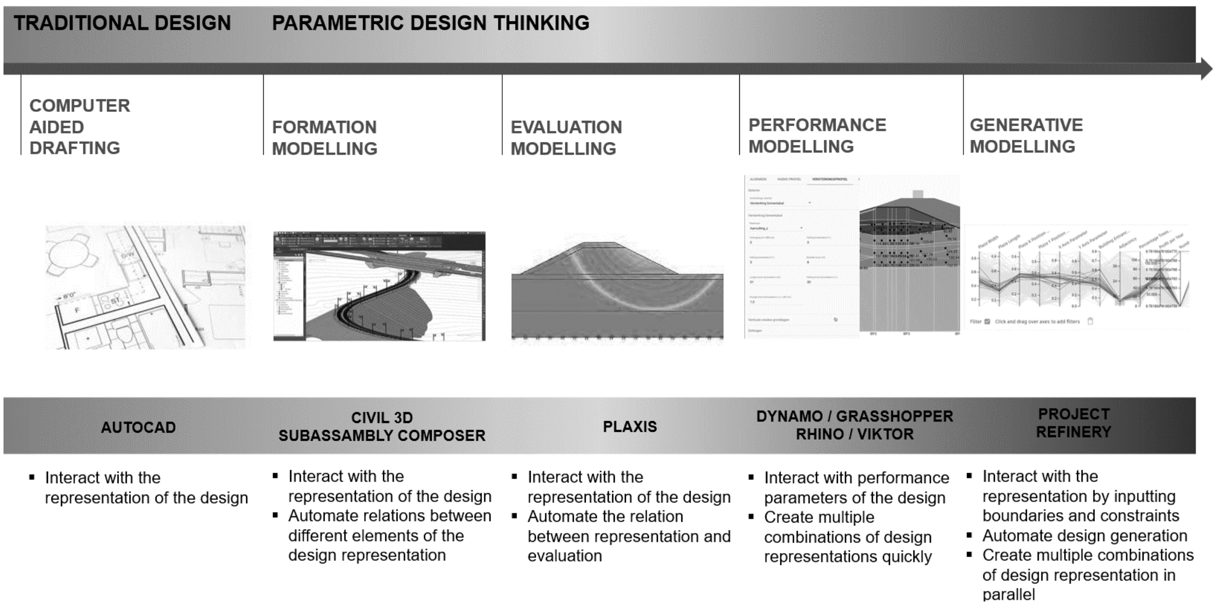


Figure 9: The difference between a traditional CAD model and a formation, evaluation, performance and generative model

Table 1 summarises the PDT typology with their corresponding dimensions, variables and functionalities. As PDT classes have different functionalities, it is implied that PDT classes also have specific factors (benefits and enablers) associated with their application. These application factors will be identified in the next section of this article.

Table 1: Typology of PDT in infrastructure engineering

Dimension	***Variables***	***Functionalities***	***Sources***
Model of engineering knowledge	1. Object-oriented models	- Store the final outcome of the design process, instead of the history of individual design operations.	Borrmann et al. (2012), Abbondati et al. (2020)
		- Generate a design using a bottom-up method of generation; first the design elements, then the system.	Harding et al. (2012), Abbondati et al. (2020)
		- Interact with data via objects.	Oxman (2006), Oxman & Gu (2015)
	2. Procedural models	- Store the history of the individual design operations, as well as the design outcome.	Shah & Mäntylä (1995), Borrmann et al. (2012), Vilgertshofer & Borrmann (2017), Biancardo et al. (2020)
		- Generate a design using a top-down method of generation; first the system (procedures), then the design elements.	Harding et al. (2012), Vilgertshofer & Borrmann (2017)
		- Interact with data via algorithms.	Oxman (2006), Oxman & Gu (2015)
Model of design	1. Single-disciplined models	- Interact with a single design discipline.	Haymaker et al. (2018)
	2. Interdisciplinary models	- Interact with multiple design disciplines.	Oxman (2017), Smith (2014), Zhang et al. (2018), Emami (2019)
		- Use interoperable data as input for the design.	Barazzetti & Banfi (2017), Zhang et al. (2018)
		- Generate interoperable data as output of the design.	Barazzetti & Banfi (2017), Zhang et al. (2018)
Process model of digital design	1. Formation models	- Interact with the representation of the design.	Oxman (2006), Oxman (2017)
		- Automate interaction between different elements of the design representation.	Oxman (2006), Raza et al. (2017), Abbondati et al. (2020)
	2. Evaluation models	- Interact with the representation of the design.	Oxman (2006), Oxman (2017)
		- Automate the relation between representation and evaluation of the design.	Salem et al. (2003), Oxman (2006), Krantz et al. (2015), Vilgertshofer & Borrmann (2017)
	3. Performance models	- Interact with generalised performance parameters of the design.	Oxman (2006), Oxman (2017)
		- Automate the relation between performance parameters and the design representation.	Oxman (2006), Biancardo et al. (2020)
		- Create multiple combinations of design representations quickly.	Biancardo et al. (2020)
	4. Generative models	- Interact with goals and constraints of the design, without defining formal qualities.	Oxman (2006), Oxman (2017), Nagy et al. (2018)
		- Automate design generation.	Oxman (2006), Oxman (2017), Nagy et al. (2018)
		- Create multiple combinations of design representation in parallel.	Oxman (2006), Oxman (2017), Nagy et al. (2018)

3.2. Identification of application factors

It is suggested that the application of PDT is dependent on several factors, specified in benefits and enablers. The main identified benefit related to PDT is its ability to speed up the design process (Aranda-Mena et al., 2009; Lu et al., 2015; Chong et al., 2016; Ghaffarianhoseini et al., 2017; Barazzetti & Banfi, 2017). Harding et al. (2012) and Zhang et al. (2018) state that resolving problems in an early design phase with design methods like PDT, costs considerably less than rectifying them later in the construction process. This principle is visualised in Figure 10, which shows that the cost of design changes is lower in the preferred design workflow using methods like PDT in comparison to the traditional design workflow. Furthermore, the ability to impact cost and functional capabilities is higher when moving from a traditional design towards a PDT design approach. Wortmann & Tunçer (2017) and Bengi (2019) state that besides cost and time, also the quality of a design can improve with design methods like PDT, as verification can be done more easily and extensively.

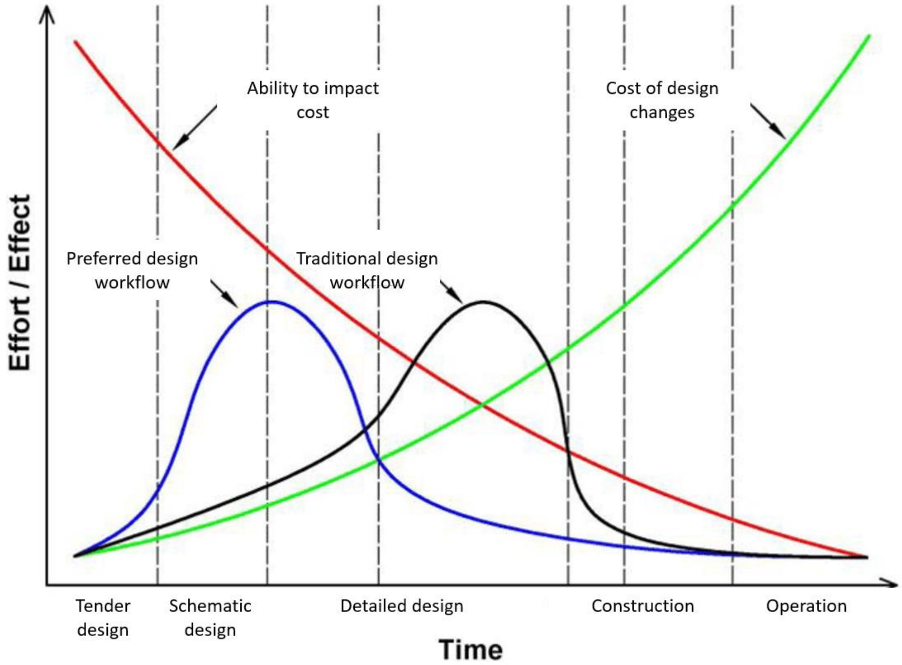


Figure 10: Moving towards a preferred design workflow using methods like PDT (Walasek & Barszcz, 2017)

The benefits of PDT are not all as direct as cost, time or quality. A more indirect benefit regards the graphic output that often accompanies PDT, which could give clear impressions of design results for (geo-) engineers, as well as other disciplines who need to get insight into design aspects (Holzer et al., 2007). When multiple disciplines get involved in the design and working practises get integrated, collaboration could be enhanced (Sacks et al., 2010; Lu et al., 2015; Santos et al., 2017; Ghaffarianhoseini et al., 2017). Furthermore, PDT could improve flexibility and decision-making in the design (Aranda-Mena et al., 2009; Bradley et al., 2016). Flexibility in this case is related to the ability to easily generate different outputs based on changing input (Wortmann & Tunçer, 2017). Improved decision-making relates to the fast feedback within the decision process (Oxman, 2017). Also, scalability in repetitive design parts could be dealt with easily, as PDT systems can cope with large amounts of data and have the ability to automate repetitive processes (Aranda-Mena et al., 2009; Sacks et al., 2010; Wortmann & Tunçer, 2017). Moreover, Bradley et al. (2016) state that PDT could enable advanced asset management capabilities of infrastructure clients, as data can be used over the whole lifecycle of an infrastructure asset. Research by Santos et al. (2017) and Oxman (2017) take this a bit further, arguing that PDT could enable the reuse of data between projects and provides a coherent model throughout the design process, thereby creating an opportunity to store design knowledge and create digital capital for the designer. The benefits associated with PDT and their related sources are summarised in Table 2.

Table 2: Benefits associated with PDT

Benefit	***Sources***
Reduce design cost and time	Aranda-Mena et al. (2009), Harding et al. (2012), Lu et al. (2015), Chong et al. (2016), Ghaffarianhoseini et al. (2017), Barazzetti & Banfi (2017), Zhang et al. (2018)
Improve verification & quality	Wortmann & Tunçer (2017), Benghi (2019)
Improve collaboration	Holzer et al. (2007), Sacks et al. (2010), Lu et al. (2015), Santos et al. (2017), Wortmann & Tunçer (2017), Ghaffarianhoseini et al. (2017)
Improve decision-making	Aranda-Mena et al. (2009), Bradley et al. (2016), Oxman (2017)
Improve flexibility in the design	Aranda-Mena et al. (2009), Bradley et al. (2016), Wortmann & Tunçer (2017), Oxman (2017)
Improve scalability in repetitive design parts	Aranda-Mena et al. (2009), Sacks et al. (2010), Wortmann & Tunçer (2017)
Store design knowledge	Bradley et al. (2016), Santos et al. (2017), Oxman (2017)

Nevertheless, several barriers can be identified for the application of PDT in infrastructure engineering. Firstly, interoperable and open data exchange facilitated by formats like the Industry Foundation Class are still being developed for infrastructure engineering (Rempling et al., 2019). Chong et al. (2016) and Barazzetti & Banfi (2017) argue that the lack of support of current standards for infrastructure projects is a major obstacle for the application of methods like PDT within the domain. More specifically, Zhang et al. (2018) states that the difficulty of integrating geotechnical information in the design system of infrastructure projects is a major barrier for PDT application, since the integration of data from non-solid earthwork structures is challenging. Besides, research by Holzer et al. (2007) and Biancardo et al. (2020) shows that the limited availability of libraries of infrastructure components and the difficulty in assigning parameters to geometries are considered obstacles when applying PDT in infrastructure engineering.

The enablers and barriers of PDT are not only technical. For example, Aish & Woodbury (2005) state that parametrisation may require additional initial effort and investment. Besides, a management strategy that focuses on the full life cycle of data within projects is considered important for design methods like PDT (Zhang et al., 2018). Talamo & Bonanomi (2020) state that the creation of a support group for digital technologies and processes at the firm level is a generally accepted enabler for digital transformation in construction. Therefore, new roles, responsibilities, and relationships within construction organisations need to be defined (Talamo & Bonanomi, 2020). When processes and technologies mature digitally, organizations should change accordingly and move toward networked organisational forms that are favourable to collaboration and integration within and between firms (Rempling et al., 2019; Talamo & Bonanomi, 2020). Research by Rempling et al. (2019) argues ‘deep specialisation in professional silos’ to be the major challenge for information integration. The research suggests that interdisciplinary capabilities of specialists play a significant role in enabling the use of design methods like PDT. Aranda-Mena et al. (2009) and Warner & Wager (2019) take this a bit further, arguing that a cultural change attitude should be reached within an organisation, incorporating innovation ecosystems, redesign of internal structures, and continuous promotion of digital maturity. Table 3 summarises the enablers and barriers identified in literature associated with PDT application.

Table 3: Enablers and barriers associated with PDT

Enabler and barrier	***Sources***
Interoperable and coherent data	Aranda-Mena et al. (2009), Chong et al. (2016), Barazzetti & Banfi (2017), Zhang et al. (2018), Georgoula & Vilgertshofer (2018), Rempling et al. (2019), Biancardo et al. (2020)
Standardization in design elements & relations	Holzer et al. (2007), Barazzetti & Banfi (2017), Georgoula & Vilgertshofer (2018), Biancardo et al. (2020)
Initial investment/effort on modelling tools and prototypes	Aish & Woodbury (2005), Becerik-Gerber & Kensek (2010), Wortmann & Tunçer (2017), Georgoula & Vilgertshofer (2018), Warner & Wäger (2019)
Management strategy on data use	Lu et al. (2015), Zhang et al. (2018), Warner & Wäger, (2019)
Networked organisational structure	Warner & Wäger, (2019), Rempling et al. (2019), Talamo & Bonanomi, (2020)
Skilled people with new roles and responsibilities	Aranda-Mena et al. (2009), Wortmann & Tunçer (2017), Warner & Wäger (2019), Rempling et al. (2019), Biancardo et al. (2020), Talamo & Bonanomi (2020)
Cultural change attitude	Aranda-Mena et al. (2009), Warner & Wäger (2019)

3.3. Framework setup

To summarise, PDT can be specified by the developed typology, which classifies PDT in sixteen classes. Also, sixteen factors, which are split in benefits and enablers/barriers, are identified on which the application of PDT classes might be dependent. Within current literature, no specification is made which links PDT classes with these factors for a specific design process.

The information from the literature expands the *PDT typology* and *Application factor* components of the proposed four-component layout (see Figure 11). The framework setup can be applied for infrastructure engineering projects. The next section presents the case studies in which *The design process* and *The fit* are specified for dike reinforcement projects.

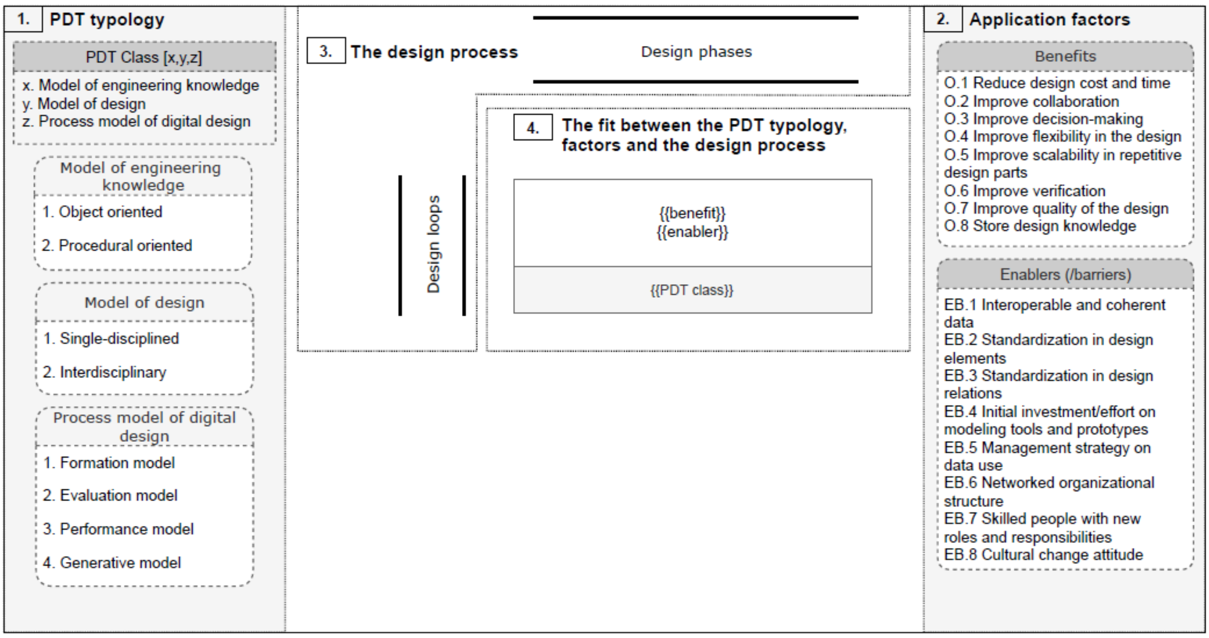


Figure 11: The framework setup, including the PDT typology and application factors

4. CASE STUDY: THE DIKE REINFORCMENT DESIGN PROCESS

In this section, the framework setup is used for the dike reinforcement design process. The results for the remaining two components, *The design process* and *The fit*, are developed and integrated in the final framework.

4.1. Identification of the design process

The design loops within the dike reinforcement design process are specified for four design phases: the tender, preliminary, detailed, and construction design phase (i.e., design changes during construction) (Halter et al., 2018), as visualised in Figure 12.

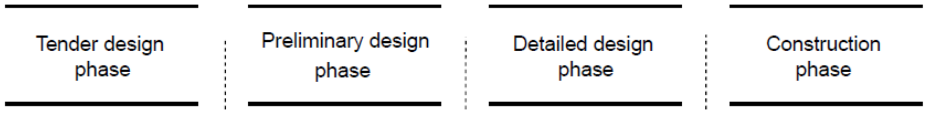
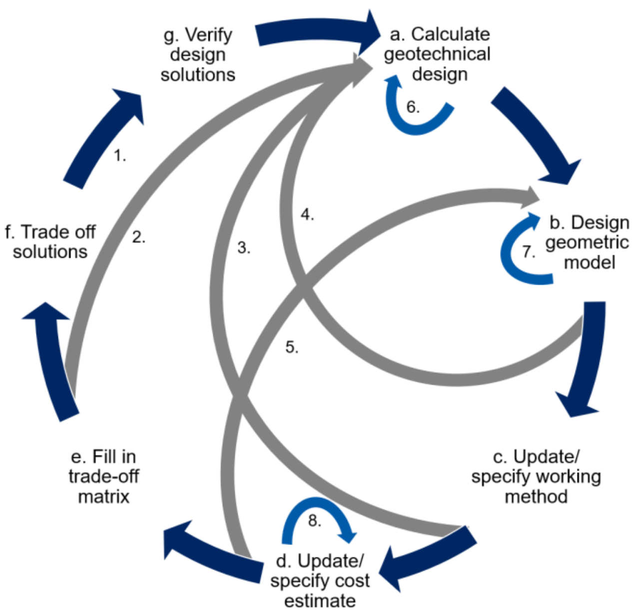


Figure 12: The design phases for a dike reinforcement project

The design loops are identified through document studies (e.g., corporate standards and design guidelines from the case studies) and expert interviews. As a result, the design is captured in Figure 13 with seven design processes (a to g) and eight design loops. The first design process is the calculation of the geotechnical design, including calculations on stability, settlement and verification with project requirements and safety standards. Secondly and partly concurrently, the geometrical design is created. This design process has the purpose of fitting the geotechnical solution within the current environment and includes activities like the gathering of information, the development of a dike profile drawing, the creation and fit-in of corridors and the verification and validation with the project requirements and geotechnical specifications. Furthermore, a working method is specified and a cost estimate is created. This includes the specification of a price book, determination of quantities, calculation of costs and verification with requirements. When several solutions are possible, a trade-off matrix is used to determine the most optimal solution. Trade-offs can be made on a variety of criteria like time, cost or CO_2 emissions. After the trade-off has been made, a final validation of the design solution is done. The different phases within the dike reinforcement design showed a lot of similarities regarding their design loops. Differences between design phases mainly resulted from a shift in emphasis on individual processes or the level of detail of the design. Nevertheless, on the abstract level of this research, it can be stated that each design phase consists of the same design loops shown in Figure 13. The validated BPMN models which underlie the design loops can be found in Appendix B.



Design loops

1. The overall design of a dike with multiple dike sections.
2. The design of multiple solutions for a dike section.
3. The geotechnical and geometrical design of a dike section, which might be altered after the working method is updated or specified.
4. The geotechnical design of a dike section, which might be altered after the geometrical model is designed.
5. The geometrical design of a dike section, which might be altered after the cost estimate is updated/specified.
6. The geotechnical design of a dike section, which might be altered by a change in data availability, assumptions, regulations, requirements or in order to find the best geotechnical solution.
7. The geometric design of a dike section, which might be altered by a change in data availability, assumptions, regulations, requirements or in order to find the best geometrical solution.
8. The cost estimate of a dike section, which might be altered by a change in data availability, assumptions, regulations, requirements or in order to find the cheapest solution.

Figure 13: The design processes (a to g) and design loops (1-8) of a dike reinforcement project

4.2. Development of the fit between the PDT typology and application factors

From the interviews (Appendix A) within the two case studies, eight benefits and nine enablers/barriers emerge as application factors. All factors found in literature as presented earlier in Table 2 and Table 3 are to some extent identified in the cases. However, they are not relevant for all PDT classes individually. No major differences are experienced in between the two case studies (Appendix C).

Recognition and support by the client is identified as a new enabler for PDT within dike reinforcement projects. Especially for procedural models, PDT class [2,y,z], recognition and support by the client is mentioned as an enabler for application of PDT. Experts stated that for dike reinforcements, clients strongly value working with recognized and validated systems. Since a procedural model can capture the design in many different ways, this recognition could be a barrier to its application. All factors related to the variables of PDT classes are summarised in Table 4.

The application factors resulted to be cumulative, in the sense that more advanced PDT classes require all factors for lower level systems plus additional factors. For example, the factors for the application of a performance model consist of the factors from a formation and evaluation model, plus the additional factors for a performance model. This is in line with the PDT typology in which a direction towards technological advanced PDT classes is identified. For a specific PDT class, application factors for all variables included in this class should be combined. The application of a system characterised as PDT class [1,1,1] would, for example, give the benefits; reduce design cost and time, improve verification, improve flexibility in the design, and improve quality of the design.

Validation of the identified application factors is performed in individual validation sessions with the participating experts. In these sessions, the application factors resulting from the coding process as explained in Section 2.2 ‘Research design’ are discussed with case study participants. Application factors that deviated from the intention of the participant, are adjusted accordingly.

Table 4: Fit between the PDT typology and application factors

Application factors	***PDT typology***							
	Model of engineering knowledge		***Model of design***		***Process model of digital design***			
	Object-oriented	***Procedural model***	***Single-disciplined***	***Inter-disciplinary***	***Formation model***	***Evaluation model***	***Performance model***	***Generative model***
Benefits								
Reduce design cost and time	✓	✓	✓	✓	✗	✓	✓	✓
Improve flexibility in the design	✗	✓	✗	✗	✓	✓	✓	✓
Improve quality of the design	✗	✗	✓	✓	✓	✓	✓	✓
Improve verification	✓	✓	✗	✓	✗	✓	✓	✓
Improve decision-making	✗	✗	✗	✓	✗	✗	✓	✓
Scalability in repetitive design parts	✗	✓	✗	✗	✗	✗	✗	✗
Store design knowledge	✗	✓	✗	✗	✗	✗	✗	✗
Improve collaboration	✗	✗	✗	✓	✗	✗	✗	✗
Enablers (/barriers)								
Standardisation in design elements	✓	✓	✗	✗	✓	✓	✓	✓
Standardisation in design relations	✗	✓	✗	✗	✗	✓	✓	✓
Management strategy on data use	✗	✓	✗	✗	✗	✗	✓	✓
Skilled people with new roles and responsibilities	✗	✓	✗	✗	✗	✗	✓	✓
Cultural change attitude	✗	✗	✗	✗	✗	✗	✗	✓
Initial investment or effort	✗	✓	✗	✗	✗	✗	✗	✗
Interoperable and coherent data	✗	✗	✗	✓	✗	✗	✗	✗
Networked organisational structure	✗	✗	✗	✓	✗	✗	✗	✗
Recognition by the client	✗	✓	✗	✗	✗	✗	✗	✗

Note. ✗ = no relation between the factor and the variable of a PDT class; ✓ = factor related to the application of the variable of a PDT class.

4.3. Framework for the application of PDT in dike reinforcement projects

From the interviews can be stated that current application of PDT classes is mostly the same in between the two case studies (Appendix D). The PDT application in the case 2 'IJsselwerken', when compared to the case 1 'Markermeerdijken', showed only an advancement from PDT class [1,1,2] and [2,1,2] towards PDT class [2,1,3] for design loop six (calculate geotechnical design). As case 2 started more recently (2020) compared to case 1 (2014), more effort was put into a management strategy on data use, skilled people with new roles and responsibilities and initial investments in PDT systems. Besides, recognition by the client is mentioned to be improved. Nevertheless, currently applied PDT classes and the preferred PDT classes do not align (Appendix D.2). The results of these case studies complete the final framework for the application of PDT in the dike reinforcement design process as presented in Figure 14 (enlarged copy and reading guide in Appendix E). Examples of applied or preferred PDT systems can be found in Appendix F.

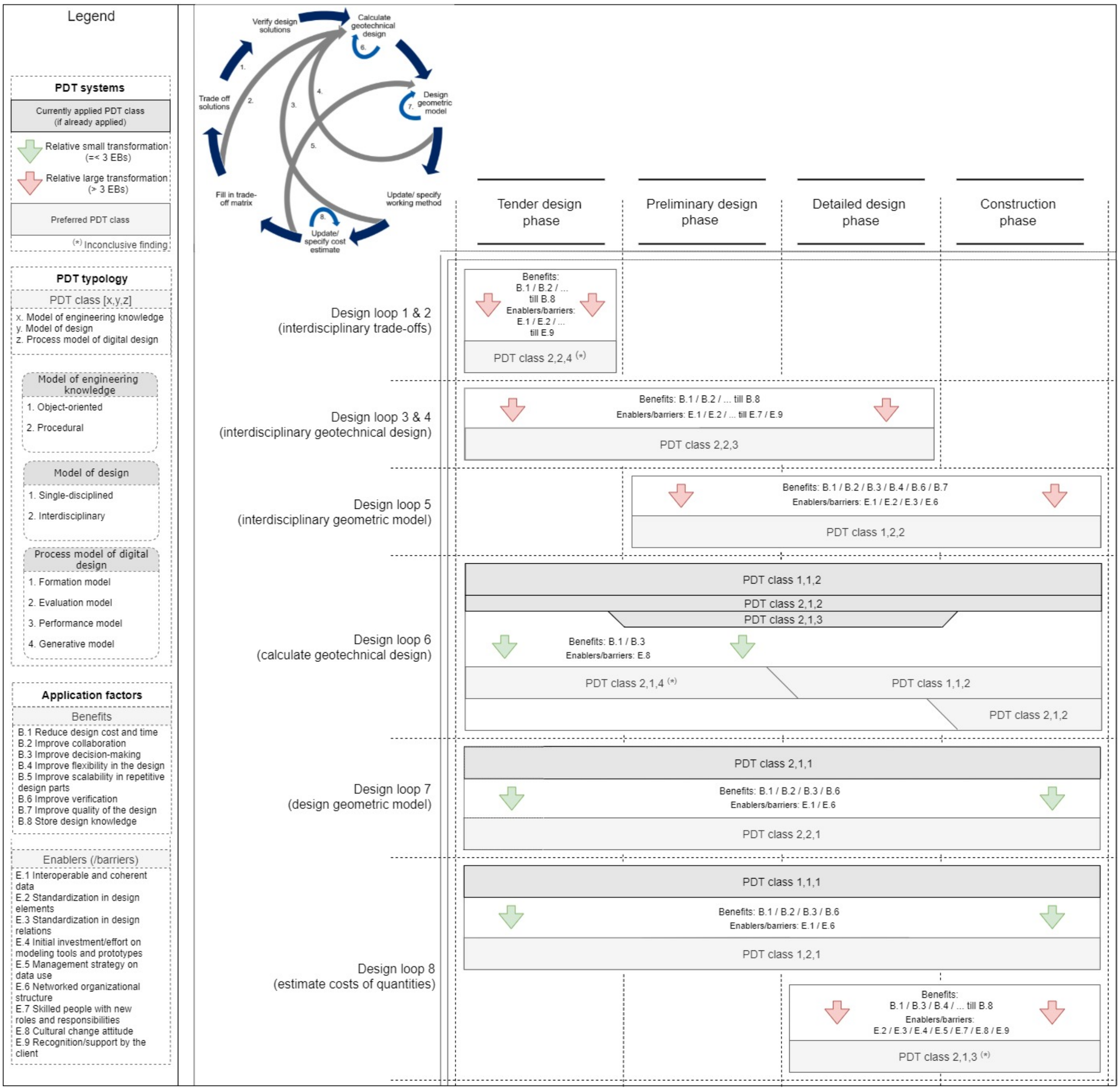


Figure 14: Framework PDT application in the dike reinforcement design process

Taking the example of design loop six (calculate geotechnical design), the framework shows the PDT classes of currently applied design systems per design phase (dark grey area), the preferred application of PDT per design phase (light grey) and the identified benefits and enablers associated with the transformation from the currently applied to the preferred PDT classes. As the application of PDT is already advanced for design loop six, transformation towards the preferred application could be made taking into account a single enabler, i.e. cultural change attitude. As indicator of a relative small transformation (=< 3 enablers), the arrow representing the transformation is green.

Figure 14 shows most preferred transformations relate to the dimension *model of design*. At the moment, PDT is only applied in design loop six till eight. No interdisciplinary PDT model, PDT class [x,2,z], is yet applied in both the case studies. Transformation towards interdisciplinary models is preferred in design loops related to all disciplines (i.e., modelling, geo-, and cost-engineering) and in all design phases. Nevertheless, incorporating interdisciplinary PDT in design loop one till five coincides with a relatively large amount of identified barriers.

Furthermore, the framework shows transformation on the dimension *process model of digital design* is mostly preferred in design loops that incorporate processes related to the geo-engineer. Generative models, PDT class [x,y,4], are preferred only in the earlier design phases, where many design alternatives for a low level-of-detail design need to be investigated simultaneously. Relatively few barriers are mentioned for generative models in design loop six. However, applying generative models for the larger design loops one or two (i.e., trade-offs) coincides with all nine enablers that need to be complied with. For application of PDT class [2,2,4] in design loops one and two, PDT class [2,1,4] in design loop six, and PDT class [2,1,3] in design loop eight, some participants had difficulties in stating their preferences for functionalities of PDT systems, resulting in inconclusive results.

For the remaining dimension, *model of engineering knowledge,* procedural models are mostly preferred, i.e., PDT class [2,y,z]. Application of procedural models is preferred in design loops related to all disciplines (i.e., geo-engineering, modelling and cost-engineering) and in all design phases. Nevertheless, for currently applied PDT systems that are object-oriented, no preference for a transformation towards a procedural model is mentioned. Even though some participants preferred procedural models for equipment optimisation in design loop eight (i.e., estimate costs of quantities), the main preferred PDT class for this design loop remains object-oriented.

Validation of the framework for the application of PDT in dike reinforcement projects is performed in two individual validation sessions and a validation workshop, as described in Section 2.2 ‘Research Design’. In the individual validation sessions, the results of the framework are discussed and reflected against expert opinions. The experts emphasised that the framework can be used for strategic application of PDT and suggested the framework development procedure could also apply to other projects than dike reinforcements, such as road design projects. No changes in the framework content resulted from these sessions. During the validation workshop, a single aspect of the framework is used to gain further insight into specific enablers. In this workshop, enabler *interoperable and coherent data* and *standardisation in design elements and relations* are further examined for design loops 3 & 4, as these are more tangible in comparison to the other enablers. Additional insights for these enablers can be found in Appendix G. The validation workshop demonstrated that design teams can gain further insights to enable the application of PDT by using the framework as a frame for discussion. Nevertheless, the validation workshop also showed the difficulty to translate the framework into concrete actions, as some participants had difficulties in grasping the implications of the enablers.

5. DISCUSSION

In this section, the results from the framework on PDT application in the dike reinforcement design process are discussed. After that, a discussion is given on the strengths and limitations regarding the use of the framework.

5.1. Discussion of results

The findings of this research suggest the existence of seventeen factors on which the application of PDT for dike reinforcements is dependent, split into benefits and enablers, and specified for each PDT class. The identified enabler *recognition and support by the client* for procedural models is currently little recognised in literature. Even though client organisations are commonly acknowledged as key actors in driving design innovation (Blayse & Manley, 2004; Adriaanse, 2007; Lindblad & Guerrero, 2020), articles do not specify the type of modelling for which recognition and support by the client is important, which can be seen as knowledge added to the body of literature.

The results suggest a gap between the scope of the currently applied PDT classes and the preferred PDT classes in the design process of dike reinforcement. Specifically, the transformation towards interdisciplinary PDT is preferred for the *model of design*. This is in line with findings in other construction domains (Singh et al., 2011; Wortmann & Tunçer, 2017; Santos et al., 2017). Results show that interdisciplinary PDT can be enabled by a networked organisational structure and interoperable and coherent data. In order to achieve a networked organisational structure, Talamo & Bonanomi (2020) identified change in organisational processes and willingness of people to work differently as the main underlying enablers. In theory, data exchange within the infrastructure engineering domain could be guaranteed by databases with Application Programming Interfaces (APIs) or platforms like the Feature Manipulation Engine (FME) (Zhu et al., 2019). However, this does not ensure interoperability. An Object Type Library (OLT) could provide interoperable information models with standardised object-type names and properties or specifications (NEN, 2020). Nevertheless, industry standards related to data exchange and standardised terminology are not yet fully suitable for dike reinforcement design projects. Especially since for dike reinforcements ‘objects’ should be defined with flexibility, as they should incorporate non-solid soil layers. Besides, an OTL for dike reinforcements should not only take into account the to be designed ‘objects’, but also released ones (e.g., soil which might be used elsewhere in the project). It is recommended to further research the possibilities for an OTL for dike reinforcements.

Especially for the design loops incorporating geo-engineering, an additional preferred transformation is found for the *process models of digital design;* from evaluation models, towards performance and generative models. The currently applied PDT systems for this discipline are already more advanced in comparison to the other design loops. When comparing this result to the literature surrounding the application of PDT in geotechnical infrastructure engineering, it can be stated that this transformation is yet little recognized for earthwork structures like dikes. While information exchange and automatised model import/export are discussed (Tschuchnigg & Lederhilger, 2019), automation in generating geotechnical design alternatives is mainly focused on solid geotechnical structures instead of earthwork structures (Fabozzi et al., 2021). This might indicate that the preferred transformation is only recently developing, and a research gap in literature exists. As some of the findings resulted to be inconclusive for advanced PDT classes, it could also imply that experts in the design team are less familiar with the benefits of such systems. As a consequence, the actual application areas of advanced PDT classes might be larger than presented in the framework. Further research on these PDT classes is needed to determine the possible enlargement of the scope of their application areas.

The result related to the dimension *model of engineering knowledge*, the preference towards procedural models, is found to be experienced in other infrastructure projects as well (Borrmann et al., 2012). The importance to first capture all object-oriented data, before transforming towards procedural modelling, is hereby emphasised (Bradley et al., 2016). The preference for design loop eight (i.e., estimate costs of quantities) towards object-oriented models deviates from findings in literature. Transformation towards procedural models for cost-engineers is recognized to support decision-making, efficiency and quality of the cost management process (Lu et al., 2016; Vigneault et al., 2020). The difference in findings might be caused by the technological difficulty to capture standardised budgeting procedures and link required cost information for earthwork projects like dike reinforcements (Raza et al., 2017). Another explanation may be that participating cost engineering experts did have a long history with traditional design methods (mean years of experience: 18.5 years (Appendix A)) and therefore might have had difficulties in grasping the benefits for a transformation towards procedural models. Additional questioning of young cost-engineers is needed to rule out this possibility.

5.2. Strengths and limitations

The presented framework in this research is based on knowledge from 40 studies (e.g., Oxman (2017), Shah & Mäntyla (1995) and Harding & Shepherd (2017)), which resulted in the PDT typology and the application factors. The introduction of a PDT typology and identification of application factors extend the scientific knowledge on the topic of PDT. Together with the procedure to study the design process of specific infrastructure engineering projects, this research shows that the proposed framework could be used to determine the application areas and application factors of PDT in these projects. Nevertheless, further research on infrastructure engineering projects different than dike reinforcements is recommended in order to increase the validity of the framework.

The qualitative case study guideline of Baskarada (2014) is followed to increase scientific rigor for the case studies. Nevertheless, the research context should be recognized for its influence. The research is limited to the subjective opinion of twelve experts in two case studies, which is not a complete representation of the industry. Besides, the pool of experts is limited to a single contractor. However, the research incorporated the main knowledge areas within dike reinforcement projects: modelling, geo-, and cost-engineering. The research could be expanded by inclusion of new expert domains like surveying and planning or inclusion of multiple contractors. The final framework, including currently applied PDT systems, preferred PDT systems, and application factors, is valid specifically for the context of the dike reinforcement case studies. However, both the used framework setup and research procedure could be used in other case studies as well.

The identified design loops and application factors per PDT class resulting from this research are broadly recognised by different disciplines within the dike reinforcement design process. Nevertheless, the identified design loops are a simplification of reality and due to the application of PDT, design loops might change. This has not been accounted for in the research. The change of the design loops after application of PDT might be subject to further research. It should also be emphasised that the application factors resulted from questioning on theoretical examples, since most PDT classes are not applied yet within dike reinforcement projects. This might have resulted in some unidentified application factors. In order to further research application factors, pilot PDT systems could be created and studied within use-cases. Furthermore, the weight criteria of each application factor is assumed to be equal. Closer inspection of the factors reveals that some factors seem to weigh heavier than others, which might affect the transformation size presented in the framework. As a result, the labelling of small and bigger transformations should be seen as an indication of the transformation size. Further research should conclude the actual transformation size related to specific enablers.

Following the discussion on strengths and limitations, it can be stated that the framework can be used to provide a basis for strategic application of PDT in infrastructure engineering. The framework is useful to determine the application areas and application factors of PDT in specific infrastructure engineering projects. Further research is needed before applying a specific PDT class.

6. CONCLUSION

Understanding the application areas of PDT in the design process of infrastructure engineering projects is a far-reaching endeavour. In order to strategically apply PDT for these type of projects, it is essential to explore the concept of PDT and to develop and formulate new disciplinary knowledge in transitioning to its general application. In this paper, a PDT typology and application factors are used to specify the application of PDT in the dike reinforcement design process. A framework is presented to (1) determine the application areas of PDT classes in the design process, and (2) identifying the main factors on which the application of PDT is dependent. The study draws the following conclusions:

- The developed framework setup (Figure 11) can act as a basis for strategic application of PDT in infrastructure engineering projects, as demonstrated for the dike reinforcement design process (Figure 14).

- The developed procedure to study the design process of a case study (Figure 3) can be used in order to scope the application of PDT in infrastructure engineering projects.
- The developed PDT typology and identified application factors (Section 3.1. Development of the PDT typology' and 3.2. Identification of application factors') further explore the concept of PDT and add new disciplinary knowledge towards its research domain.
- In the design process of dike reinforcements, gaps exist between the scope of currently applied PDT and preferred PDT. Various factors are associated with the transformation to bridge these gaps. Several recommendations can be provided to contractors that want to apply PDT in the design process of dike reinforcements, see section 7.2.

7. RECOMMENDATIONS

7.1. Recommendations for further research

This research could be expanded by integrating case studies of multiple contractors and inclusion of new expert domains like surveying and planning. Additional research could also be aimed at getting a deepened understanding of specific relations or factors within the presented framework. Furthermore, pilot PDT systems can be created and studied in use-cases to test and evaluate the application of PDT classes empirically. Finally, the framework setup could be used in the design process of other infrastructure engineering projects in order to determine the external validity and generalisability of the proposed framework setup and used procedure.

7.2. Recommendations for dike reinforcement contractors

The first recommendation for contractors that want to apply PDT in the design process of dike reinforcement regards the preference of all disciplines towards a high integration within the models of design. Since this transformation is generally preferred, it is recommended to prioritise the enablers linked to the interdisciplinary PDT class. These enablers constitute the basis for a PDT system reducing design cost and time, and improving decision-making, collaboration, flexibility, and design quality & verification. Focus is need on: a networked organizational structure, standardisation in design elements, and interoperable and coherent data. In the case studies, these enablers are at least partly experienced (e.g., by the existence of a setup for a corporate strategy on a digital design and by the involvement of enterprise architects, who are responsible for ensuring the corporate strategy uses proper technology systems to achieve its goals). It is recommended to also create awareness and stimulate employees willingness towards transformation of advanced PDT, as not all experts in the design team are familiar with the benefits of such systems. Furthermore, interoperable and coherent data between the different design disciplines in the case studies is still relatively low: little standardised object-type names, properties or specifications did yet exist (e.g., modellers were using object codes resulting from the systems engineering approach, while cost-engineers used different codes for the same object). An OTL could facilitate a common language between disciplines and projects. Preferably, an OTL is set up by industry standards. Due to the arrival of the NTA8035, NEN2660, and the development of CB-NL, there is consensus on basic principles that must be met in order to share information and facilitate exchange within the industry. Nevertheless, these industry standards are not yet fully suitable for dike reinforcement design projects, since they do rarely take into account released 'objects' like soil to be used elsewhere in the project, and because they are less suitable to described objects with high flexibility (in order to describe soil layers). It is recommended to further research the possibilities for an OTL for dike reinforcements.

Secondly, since the integration of large design loops coincides with a relatively large amount of enablers that need to be complied with, it is recommended to start by applying PDT on smaller design loops. Incorporating PDT in design loops like *design loop six (i.e., geotechnical design), seven (i.e., geometrical design)* or *eight (i.e., cost calculations)*, coincides with a smaller amount of enablers that need to be complied with, and still offers several benefits. However, integration should still be considered. For small design loops, this could be guaranteed with the creation of several databases, APIs or platforms like FME to transfer data between systems. Since enablers are considered cumulative, starting the application of PDT on smaller design loops while considering data transfers, could form the basis for a transformation towards the larger application of integrated PDT.

Finally, it is recommended to focus on the application of performance, generative, and procedural models for the design process related to geo-engineering. As design decisions from this discipline provide fundamental input for the processes later in the design, the ability to evaluate more design alternatives and thereby reduce design risks could generate most benefits. Since procedural models capture knowledge in their design system, they can be used by geo-engineers to build up digital capital. As a result, geo-engineers spend less time performing calculations or re-designing dike sections, allowing more attention to interpretations of results and integration with other disciplines.

8. ACKKNOWLEDGEMENTS

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Appendix A: Interview setup

This appendix contains the interview setup of the in-depth, semi-structured case study interviews. Since the interviews are semi-structured, it is allowed to elaborate on the things brought up during the interview as a result of what the interviewee said. In this way, individuals' thoughts and perceptions on specific PDT classes are explored. The interviews are conducted at a maritime and inland infrastructure contractor in the Netherlands. Three experts disciplines from two case studies are consulted; geo-engineers, modellers and cost-engineers. In total, four geo-engineers (mean years of experience: 8.6 ± 4.8 years), four modellers (mean years of experience: 9.8 ± 6.4 years), and four cost-engineers (mean years of experience: 18.5 ± 13.8 years) participated in the research.

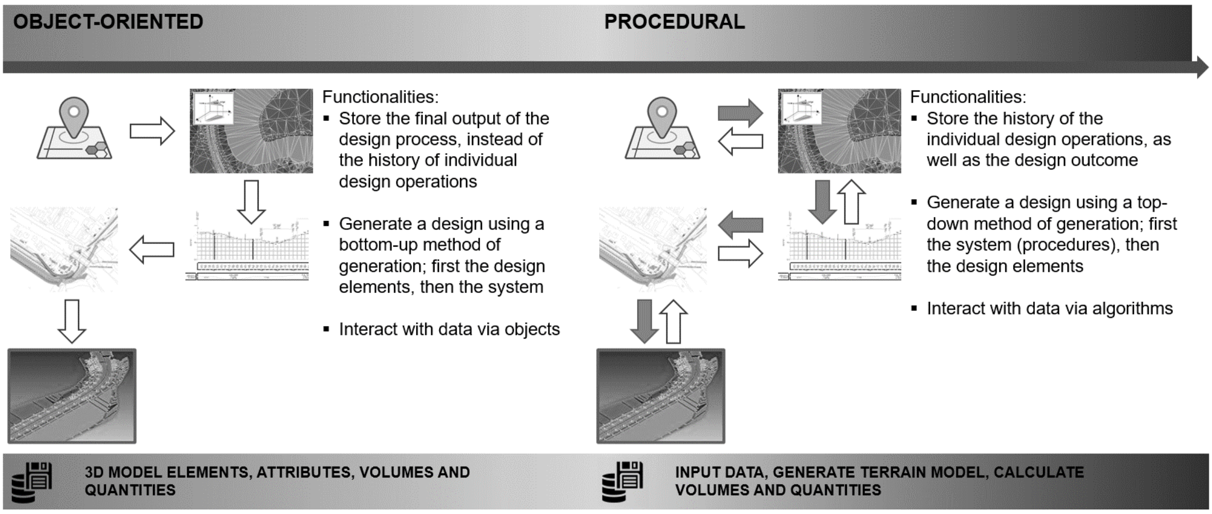
PDT classes are during the interviews described by their functionalities and PowerPoint slides with examples are used to make those concrete. Questions are structured around the use of these functionalities as well as the perception of organizational and contextual factors that may affect this use. In this research, both currently applied PDT systems and preferred PDT systems are questioned for all design phases. Below, the setup for questioning and an example of the PowerPoint slides explaining the PDT classes are shown.

Preparation: Take as-is scenario as basis for a specific discipline and apply the questions on the currently applied design system. Test against advancement of the three dimensions in the PDT typology:

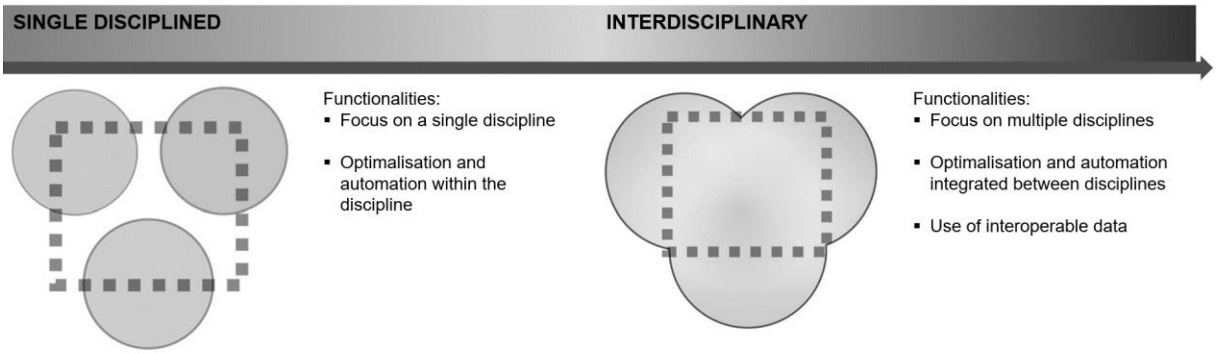
- Advancement in model of engineering knowledge (with the help of PDT application examples, slide 1 (Appendix A.1))
    - Do you think it would be interesting to use {functionality} in this design process? Why?
    - What would enable the use of this functionality? / What barriers do you think will arise when trying to apply this functionality?
- Advancement in model of design / Enlargement of design loop (with the help of slide 2 and the visual design loops in slide 3 (Appendix A.2))
    - Do you think it would be interesting to incorporate {design process} in this parametric system? Why?
    - What would enable the integration of this design process? / What barriers do you think will arise when trying to integrate this design process?
- Advancement in the process model of digital design (with the help of PDT application examples, slide 3 (Appendix A.3))
    - Do you think it would be interesting to use {functionality} in this design process? Why?
    - What would enable the use of this functionality? / What barriers do you think will arise when trying to apply this functionality?

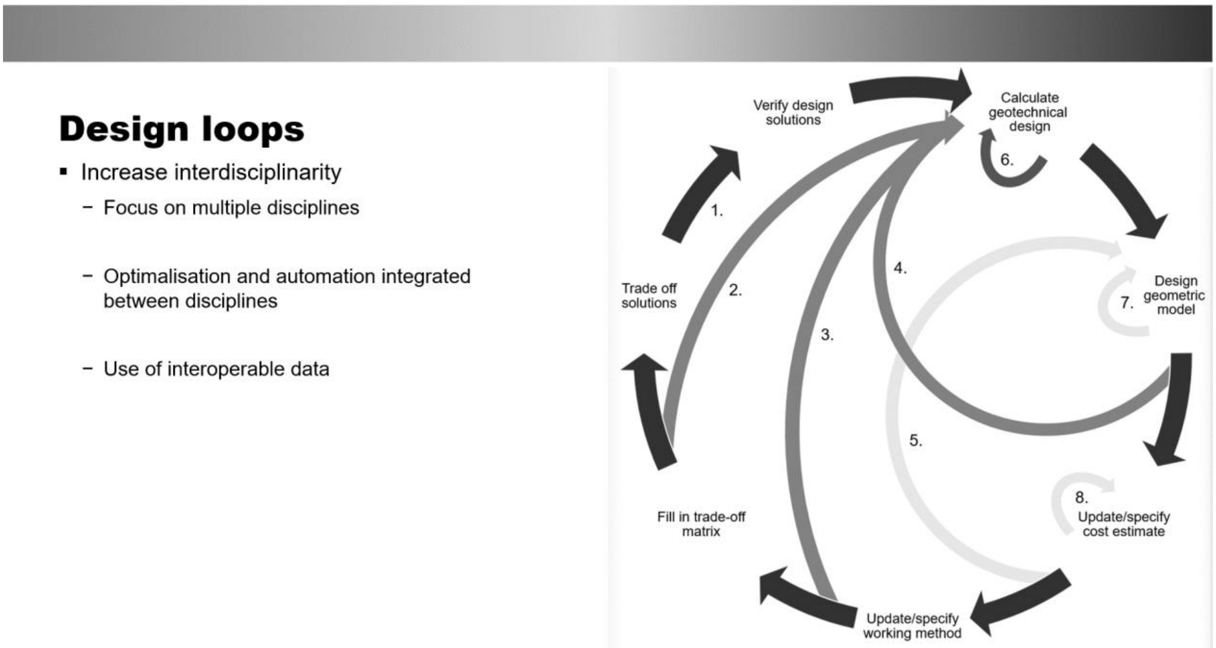
Questions are repeated for each design phase.

Appendix A.1: Interview slide model of engineering knowledge

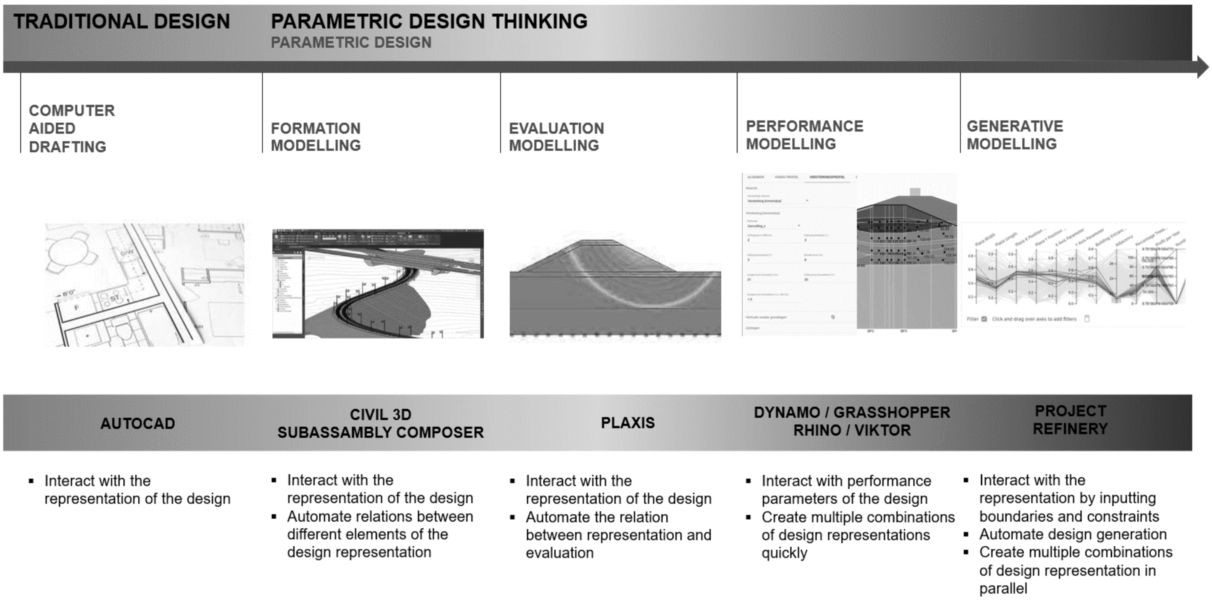


Appendix A.2: Interview slides model of design





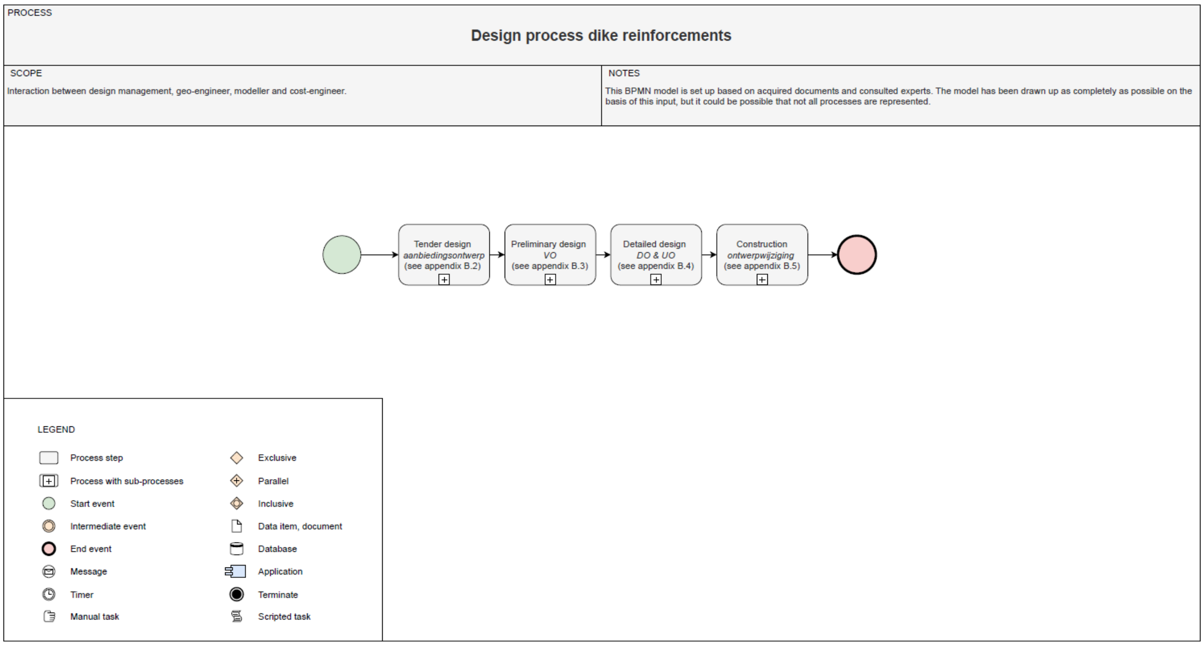
Appendix A.3: Interview slide process model of digital design



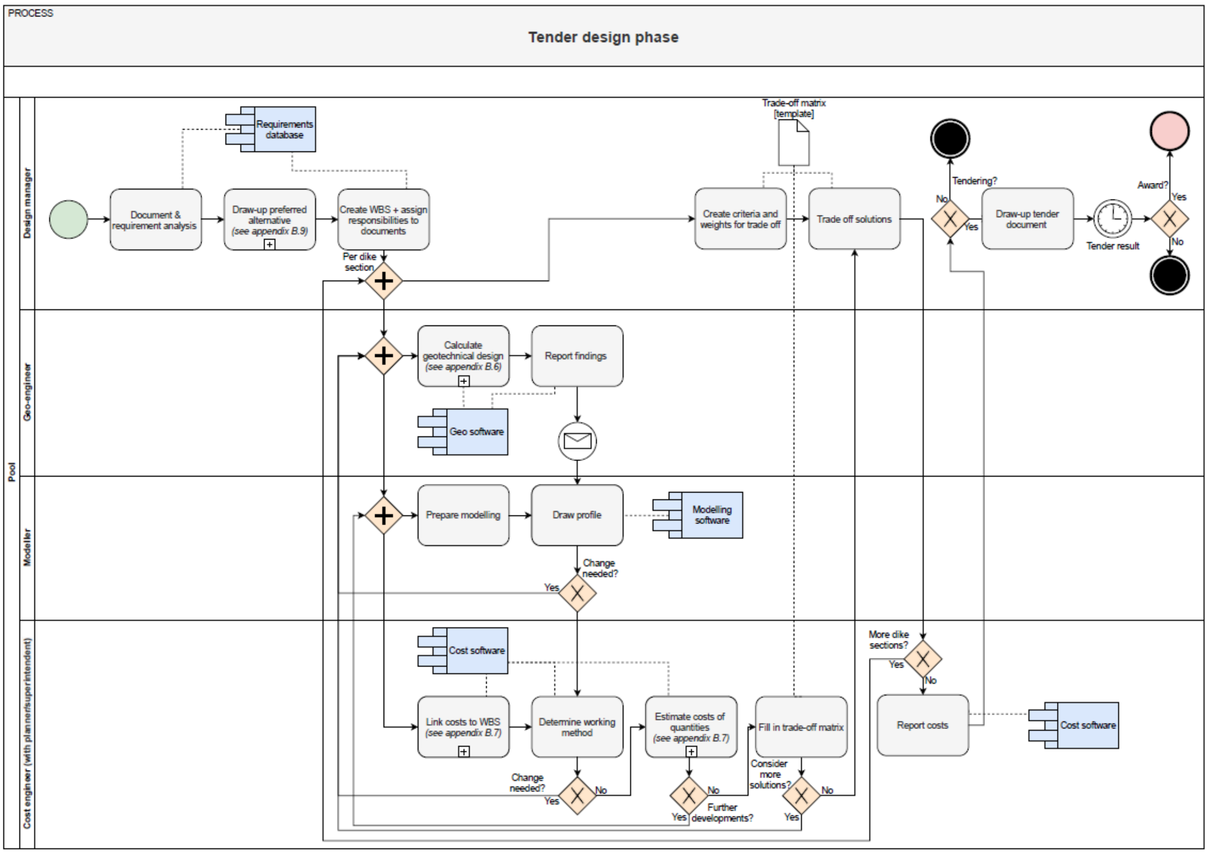
Appendix B: The dike reinforcement design process in a BPMN model

This appendix contains the BPMN models which resulted from interviews and document studies on corporate guidelines and industry standards. Design processes are specified for each design phase (Appendix B.1 – Appendix B.5). Furthermore, for some design processes, sub-processes are specified (Appendix B.6 – Appendix B.9). Design loops can be identified by the arrows within the BPMN model that together form a circle.

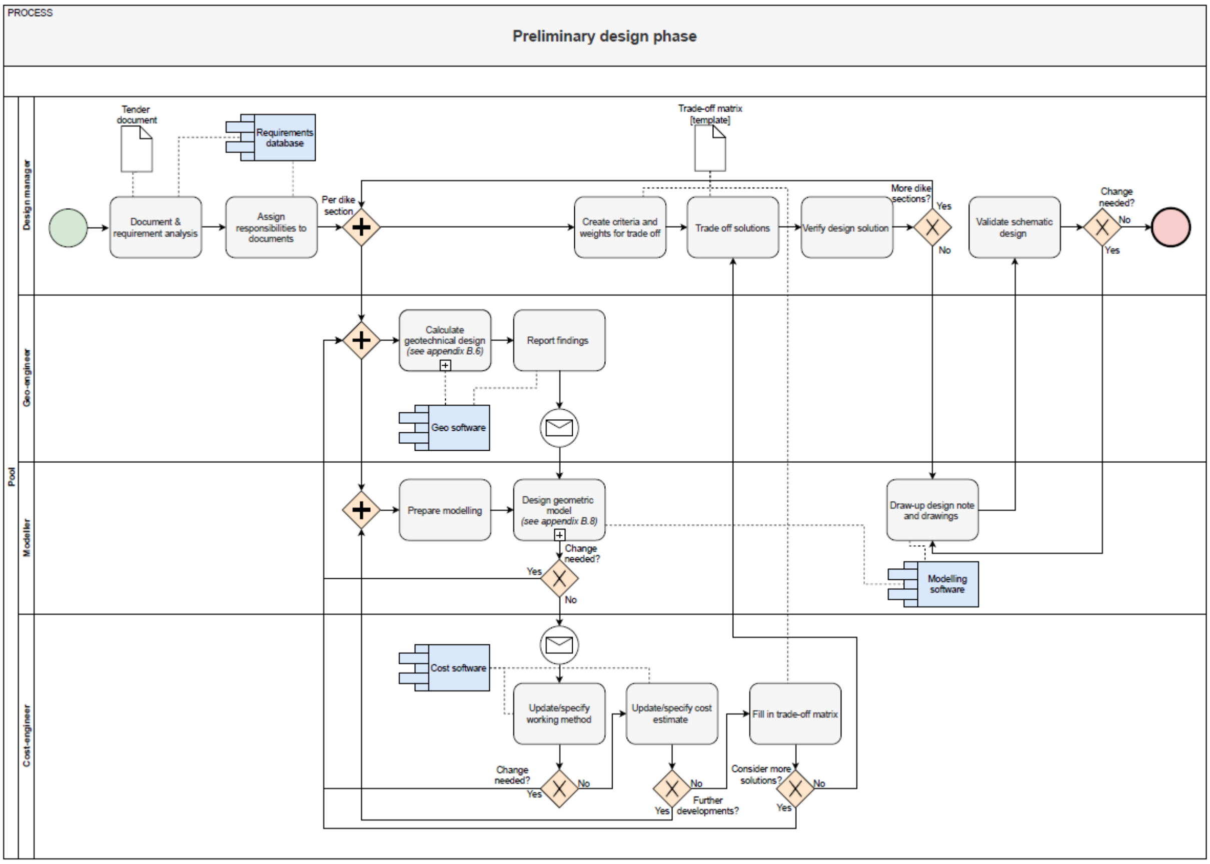
Appendix B.1: The design phases



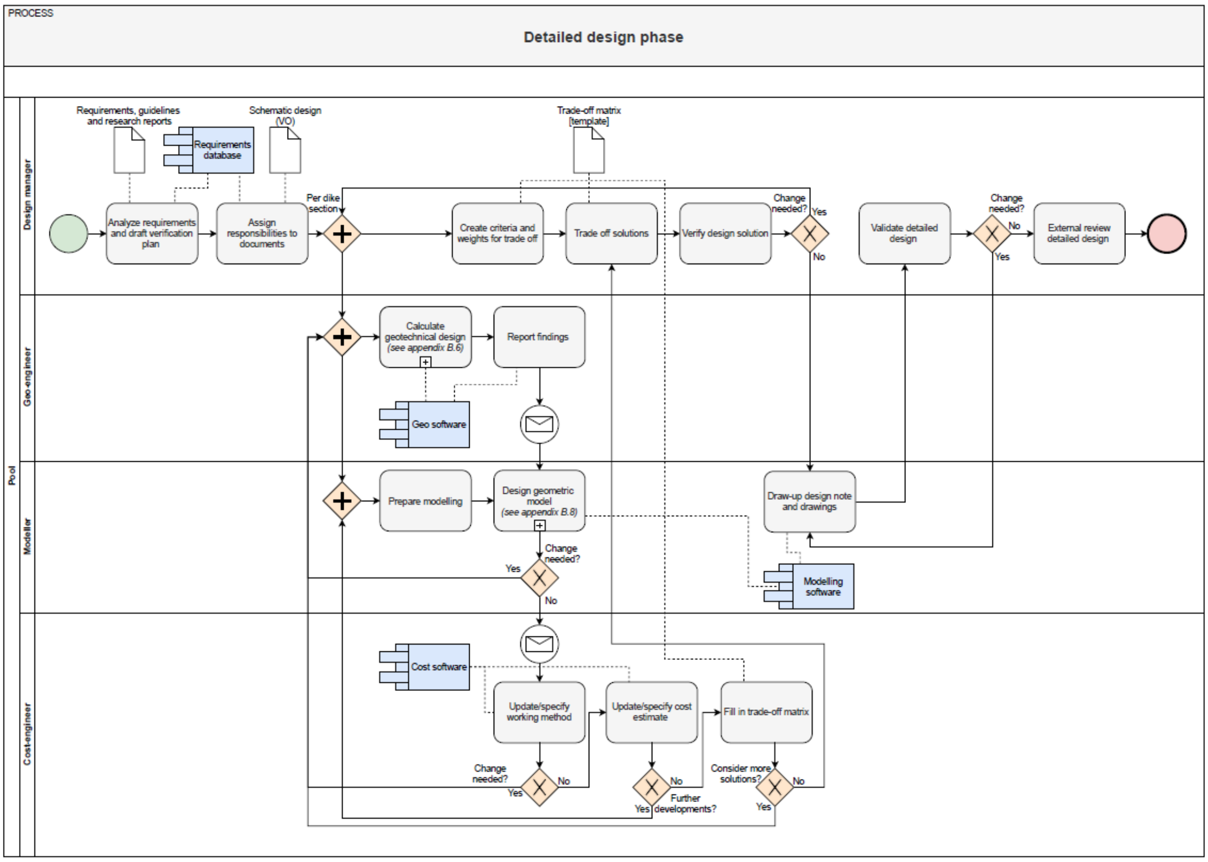
Appendix B.2: The tender design phase



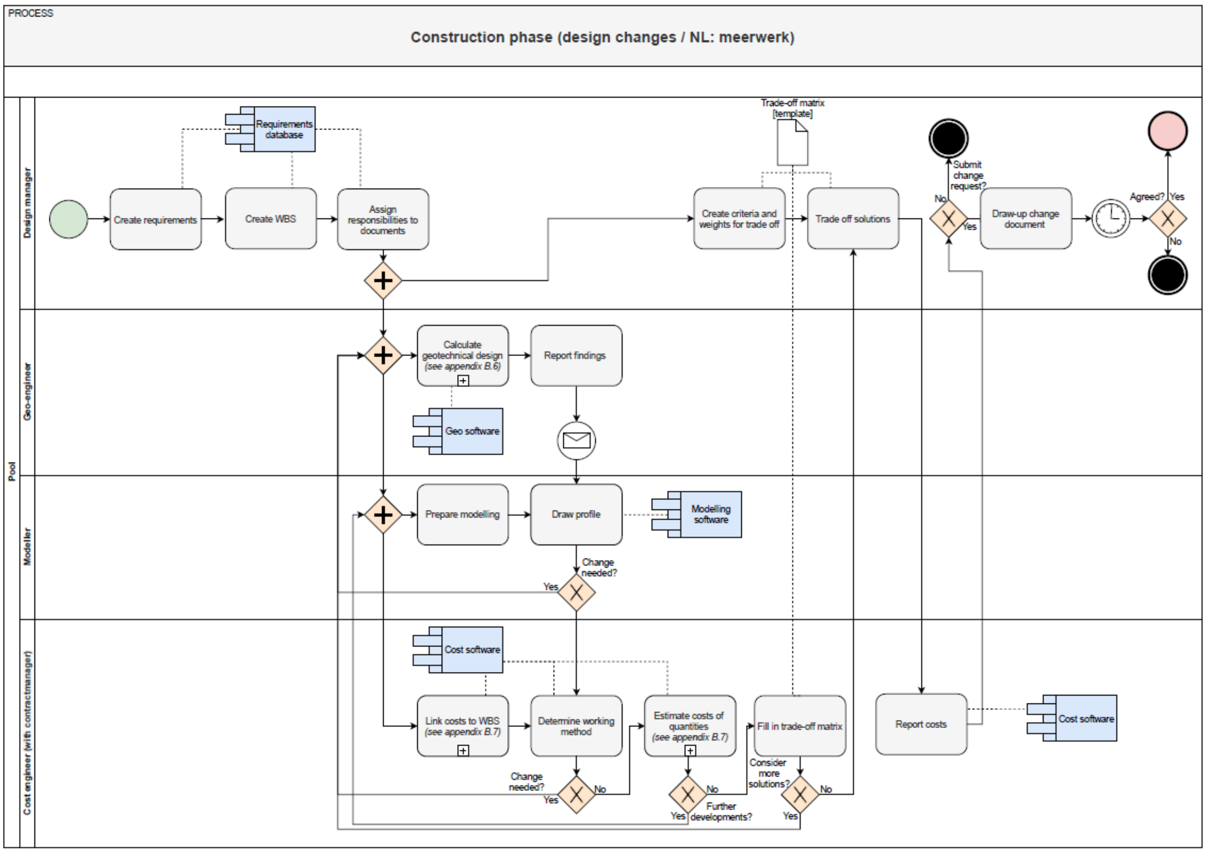
Appendix B.3: The preliminary design phase



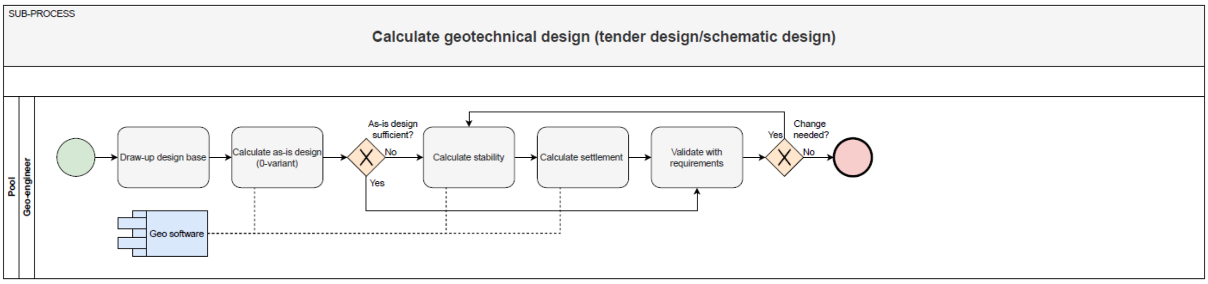
Appendix B.4: The detailed design phase

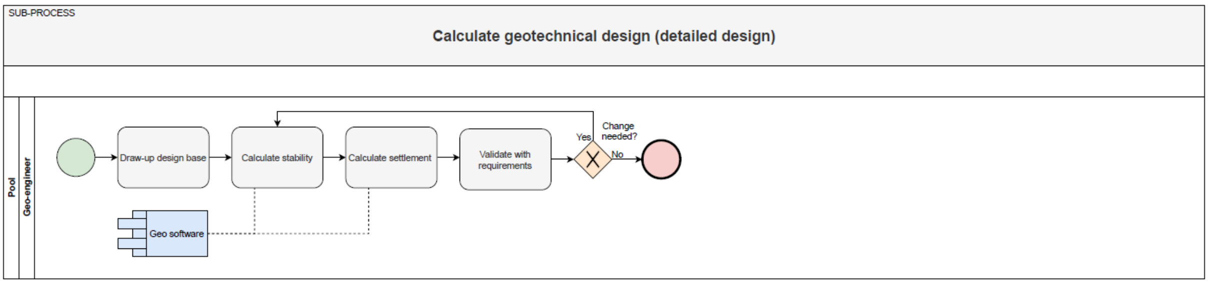


Appendix B.5: The construction design phase

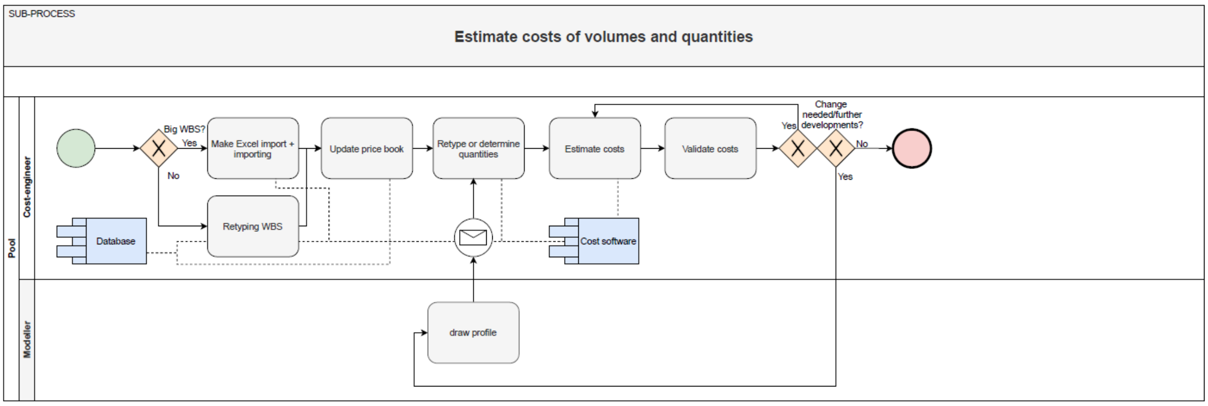


Appendix B.6: Sub-process, calculate geotechnical design

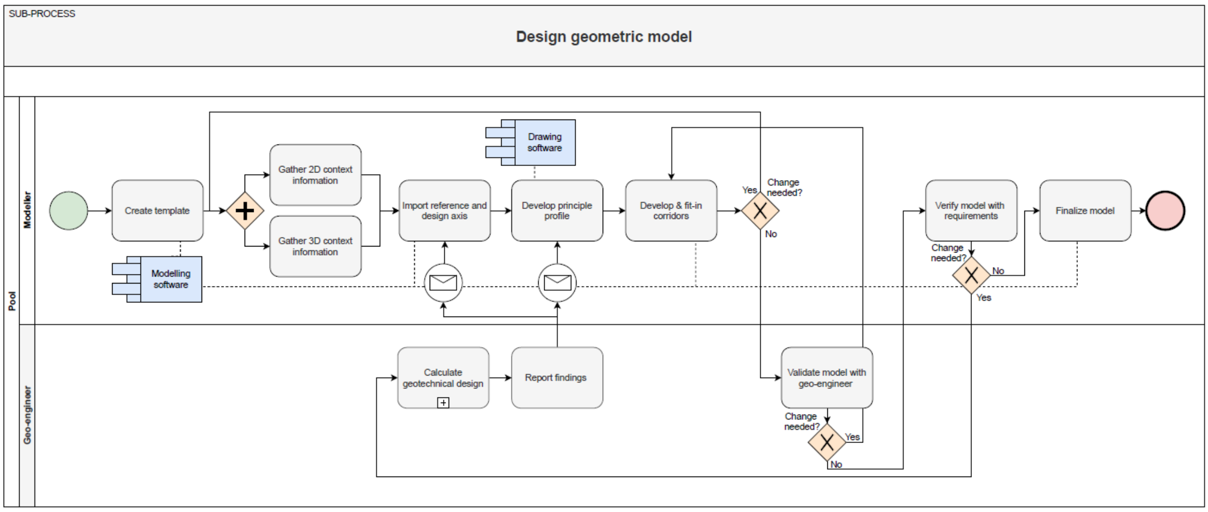




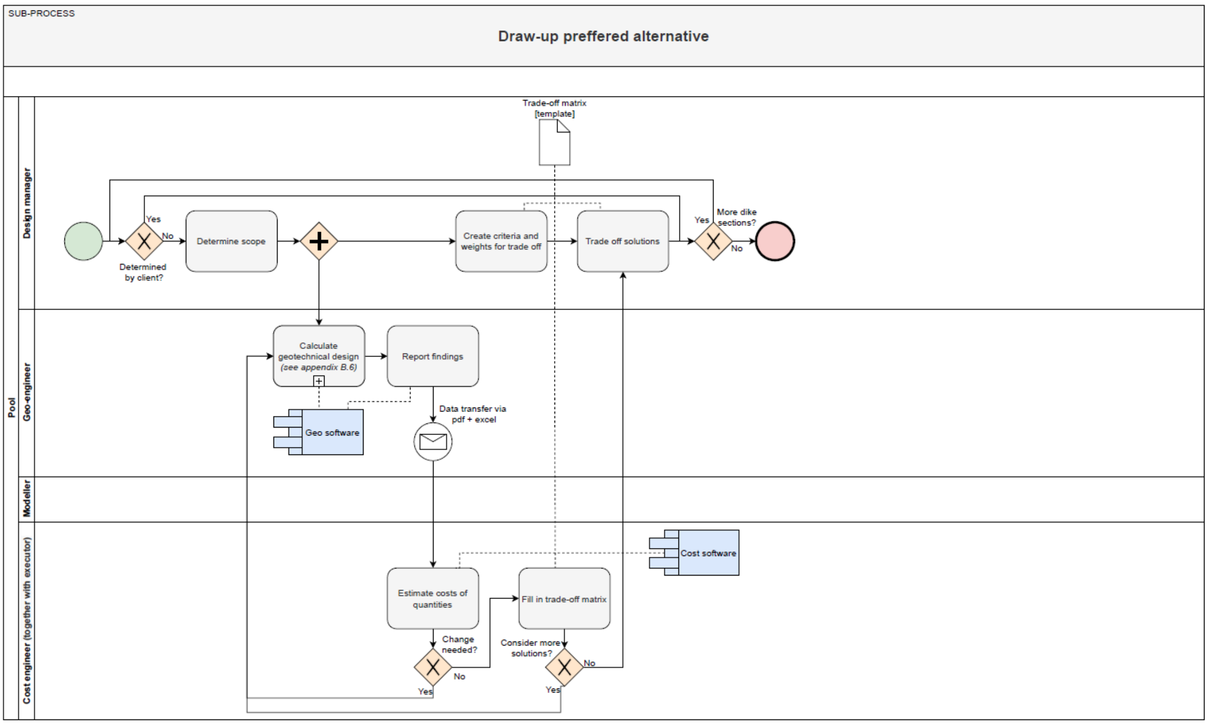
Appendix B.7: Sub-process, estimate costs of volumes and quantities



Appendix B.8: Sub-process, design geometric model



Appendix B.9: Sub-process, draw-up preferred alternative



Appendix C: Case study analysis of the fit between application factors and the PDT typology

This appendix contains the cross-case analysis of the fit between application factors and the PDT typology in the two case studies. Differences in between the relations are marked red. As can be seen in the table, differences only occur at the benefits. They always concern a relations that is present in case 1 and absent in case 2. A possible explanation might be the fact that the project of case 2 started more recently (2020) than the project of case 1 (2014), and the design is still ongoing. Therefore, some benefits of PDT might not yet be experienced.

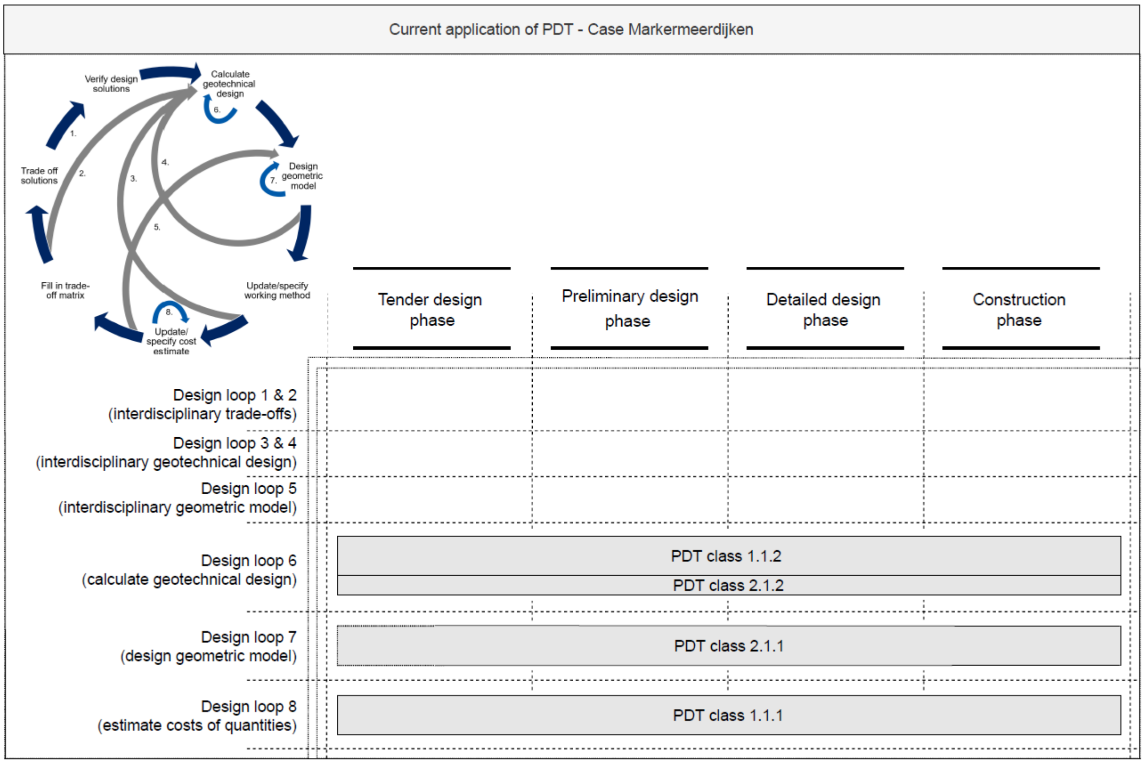
Application factors	*Model of engineering knowledge*				*Model of design*				*Process model of digital design*							
	Object-oriented		*Procedural model*		*Single-disciplined*		*Inter-disciplinary*		*Formation model*		*Evaluation model*		*Performance model*		*Generative model*	
Case	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Benefits																
Reduce design cost and time	✓	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓
Improve flexibility in the design	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓
Improve quality of the design	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Improve verification	✓	✓	✓	✓	✗	✗	✓	✗	✗	✗	✓	✗	✓	✓	✓	✓
Improve decision-making	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓
Scalability in repetitive design parts	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Store design knowledge	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Improve collaboration	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
Enablers (/barriers)																
Standardisation in design elements	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓
Standardisation in design relations	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓
Management strategy on data use	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓
Skilled people with new roles and responsibilities	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓
Cultural change attitude	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓
Initial investment or effort	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Interoperable and coherent data	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
Networked organisational structure	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
Recognition by the client	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

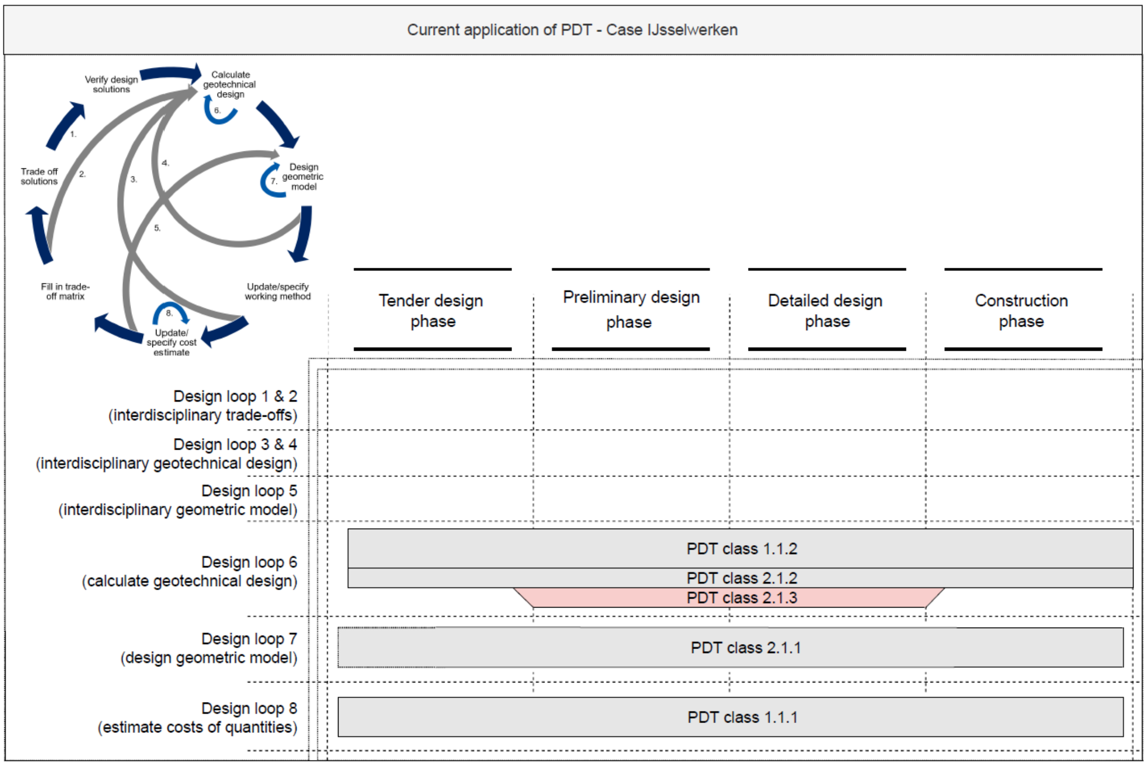
Note. ✗ = no relation between the factor and the variable of a PDT class; ✓ = factor related to the application of the variable of a PDT class; ✗✓ = difference in results from the cross-case analysis.

Appendix D: Case study analysis of the PDT application

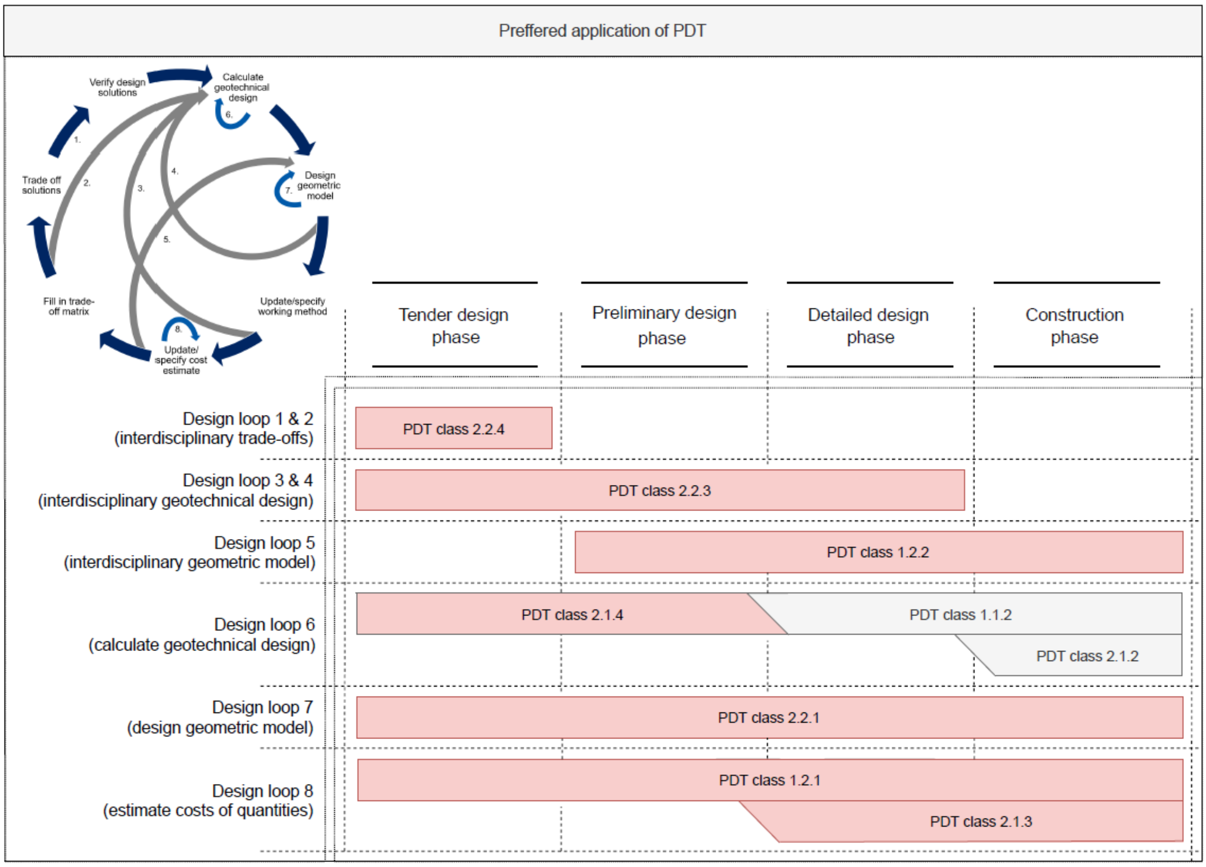
This appendix contains the cross-case analysis of the current PDT applications in the two case studies (Appendix D.1) and the identified preferred PDT applications (Appendix D.2). Examples of the identified PDT systems can be found in Appendix F. Differences in between the current application of PDT between the two cases are marked red.

Appendix D.1 – Cross-case analysis



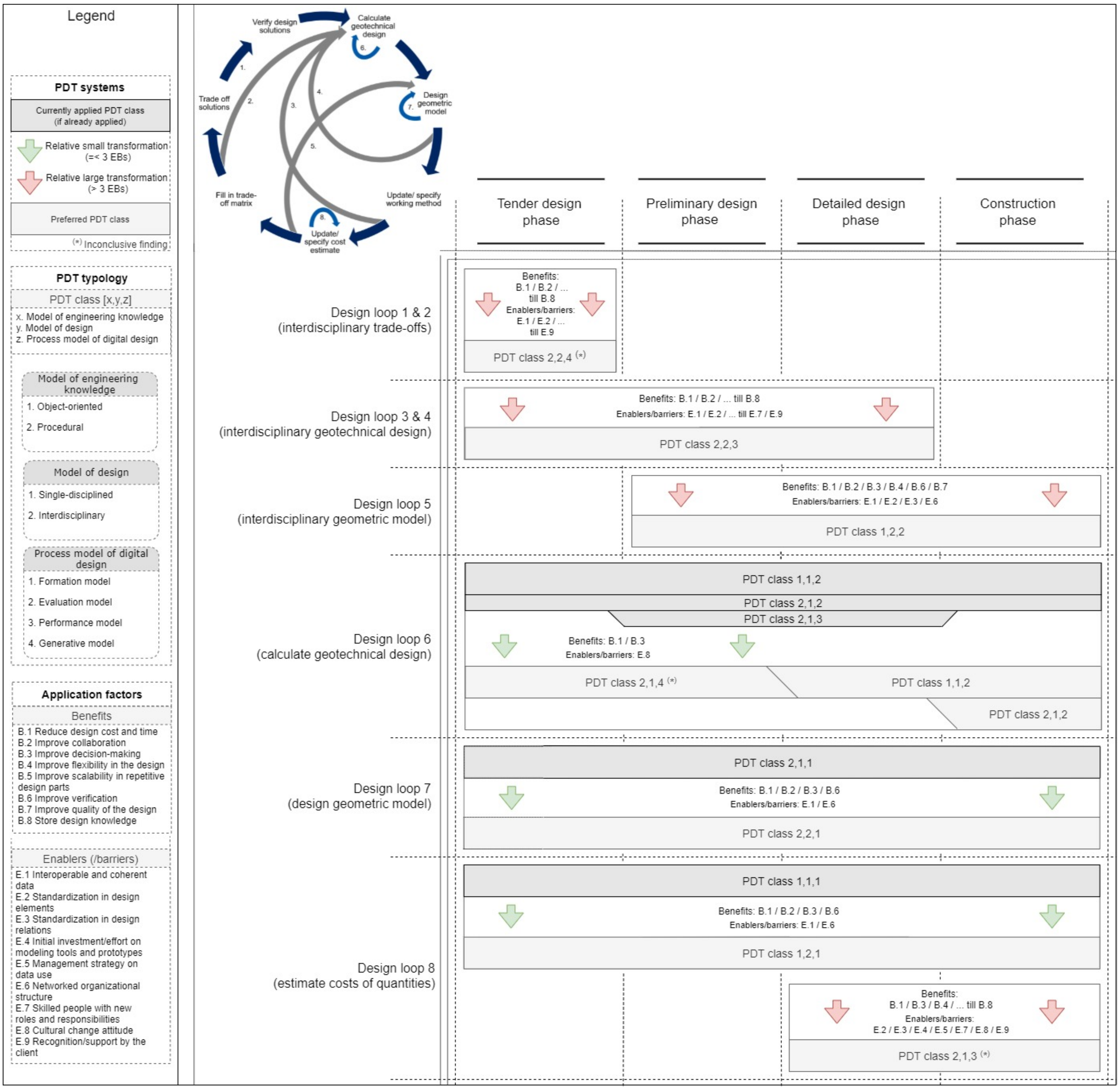


Appendix D.2 – Analysis between currently applied PDT and the preferred application of PDT
The preferred application of PDT shows a lot of differences when compared to the current application of PDT, marked red. The participants had difficulties with separating the case study from their earlier executed projects. Therefore, the data resulting from the two cases are combined.



Appendix E: Framework PDT application in the dike reinforcement design process

This appendix contains an enlarged version and elaborate explanation of how the framework should be read.



Reading the framework results should be done in four consecutive steps.

1. Check the application area of your interest within the design process. The application area in the framework is defined as the intersection of a design phase (e.g., tender-, preliminary design phase) and a design loop (numbered 1 to 8). The definitions of the design phases and design loops can be found in section *4.1. Identification of the design process*.
2. Check the currently applied PDT system within the application area. The currently applied PDT systems are labelled dark grey and positioned at the top of each application area. Descriptions of these systems can be found in *Appendix F*. For design loops six till eight, several PDT systems are already in use. Taking the example of design loop six (calculate geotechnical design), the framework shows the PDT classes of currently applied systems are PDT class [1,1,2], PDT class [2,1,2] and PDT class [2,1,3]. The definition of these PDT class can be found in section *3.1. Development of the PDT typology*. In *Appendix F* can for example be found that the used software platforms VIKTOR and BAAS fall into the category of PDT class [2,1,3]. Their tooling for dike reinforcements includes functionalities like automatic subsurface schematization, 'building blocks' with performance parameters for dike reinforcements and automated stability and settlement calculations. Using this software, a large number of geotechnical design variants can be calculated relatively quickly. For design loops one till five, no PDT systems are yet applied in the case studies.
3. Check the preferred PDT system within the application area, which are based on interviews with specialists. The preferred PDT systems are labelled light grey and positioned at the bottom of each application area. Descriptions of these systems can also be found in *Appendix F*. For design loop one till five, not all design phases have a preferred PDT system. For example for design loops one & two, the application of the PDT system classified as PDT class [2,2,4] is only preferred in the tender design phase. During the interviews, this PDT class is mentioned to be useful for weighing of preferred alternatives during the tender design phase in order to minimise tender risk. Examples of mentioned parameters to be included are: rejected failure mechanism, soil condition, price, space use and risks (*Appendix F)*. During the preliminary design phase till the construction phase, application of a PDT system is not preferred for design loops one and two.
4. Check the application factors associated with the transformation within the application area. These application factors are defined as the benefits and enablers associated with moving from the currently situation, towards the application of the preferred PDT system and labelled with B- and E-numbers. The definition of these benefits and enablers can be found in section *3.2. Identification of application factors*. For example for design loop seven, the preferred PDT application can be enabled by the use of interoperable and coherent data and the creation of a networked organisational structure. Based on this knowledge, a strategy can be defined to facilitate or stimulate these enablers, so PDT class [2,2,1] can be applied.

Appendix F: Examples of PDT systems

This appendix contains examples of the PDT systems described in the framework. These examples are identified during interviews for the two case studies in this research.

System description	*PDT class [x,y,z]*	*Functionalities*
Currently applied		
Design loop 6 - D-stability and Plaxis: The D-stability program has been developed for the design and stability control of embankments and dikes on soft ground. Plaxis is a programme that performs finite element analyses within the realm of geotechnical engineering, including deformation and stability analysis.	[1,1,2]	- Interact with the representation of the design. - Automate the relation between representation and evaluation of the design. - Store the final outcome of the design process, instead of the history of individual design operations. - Generate a design using a bottom-up method of generation; first the design elements, then the system. - Interact with data via objects. - Interact with a single design discipline.
Design loop 6 - HEDSET: a custom made Excel sheet in which settlement calculations can be performed quickly. It is based on a numeric model that relates representation and evaluation. It gives grip on what needs to be calculated and the knowledge behind the calculations, since relations in the system are known.	[2,1,2]	- Automate the relation between representation and evaluation of the design. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with a single design discipline.
Design loop 6 - BAAS/VIKTOR: both BAAS and VIKTOR are platforms which are still in development or already partly deployed. Their tooling for dike reinforcements includes functionalities like automatic subsurface schematization, 'building blocks' with performance parameters for dike reinforcements and automated stability and settlement calculations. Large number of geotechnical design variants can be calculated relatively quickly.	[2,1,3]	- Interact with generalised performance parameters of the design. - Automate the relation between performance parameters and the design representation. - Create multiple combinations of design representations quickly. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with a single design discipline.
Design loop 7 - Subassembly Composer: the Autodesk Subassembly Composer for Autodesk Civil 3D provides an interface for composing and modifying complex subassemblies. Design elements are related via mathematical equations which can be altered when needed.	[2,1,1]	- Interact with the representation of the design. - Automate interaction between different elements of the design representation. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with a single design discipline.
Design loop 8 - Metacom: calculation software with a large cost library that is used for parametric creation of budgets and cost estimates. Using the cost library, standardisation in cost calculations is guaranteed and repetitive parts of calculations are automated.	[1,1,1]	- Automate interaction between different elements of the design representation. - Store the final outcome of the design process, instead of the history of individual design operations. - Generate a design using a bottom-up method of generation; first the design elements, then the system. - Interact with data via objects. - Interact with a single design discipline.

System description	***PDT class [x,y,z]***	***Functionalities***
Preferred		
Design loop 1/2 - a PDT system for weighing of preferred alternatives. Examples of parameters: rejected failure mechanism, soil condition, price, space use and risks.	[2,2,4]	- Interact with goals and constraints of the design, without defining formal qualities. - Automate design generation. - Create multiple combinations of design representation in parallel. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with multiple design disciplines.
Design loop 3/4 - a PDT system incorporating interdisciplinary input for geotechnical calculations. Examples of possible systems: a more extensive VIKTOR or BAAS system, incorporating interdisciplinary design parameters. Or a system supporting smart use of existing and released soil with a cost estimations of geotechnical solutions based on logistical parameters. Or a system weighing price and time concerning settlement accelerating measures against elevation with sand. Or a system which gives a rough evaluation on the integration of the geotechnical solution with the existing situation with an automated classification of sub-sections of dikes based on subsurface and environment characteristics.	[2,2,3]	- Interact with generalised performance parameters of the design. - Automate the relation between performance parameters and the design representation. - Create multiple combinations of design representations quickly. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with multiple design disciplines.
Design loop 5 - a PDT system which for example gives a rough evaluation on costs of the geometrical solution during modelling, so the modeller could get an indication of cost consequences of a solution.	[1,2,2]	- Interact with the representation of the design. - Automate the relation between representation and evaluation of the design. - Store the final outcome of the design process, instead of the history of individual design operations. - Generate a design using a bottom-up method of generation; first the design elements, then the system. - Interact with data via objects. - Interact with multiple design disciplines.
Design loop 6 - a PDT system conducting a lot of geotechnical calculations in parallel, while automatically altering the input parameters in order to better evaluate risks and more extensively search the solutions space.	[2,1,4]	- Interact with goals and constraints of the design, without defining formal qualities. - Automate design generation. - Create multiple combinations of design representation in parallel. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with a single design discipline.

System description	*PDT class [x,y,z]*	*Functionalities*
Design loop 6 - HEDSET: as explained above. This system is also applied in the preferred situation.	[2,1,2]	- Automate the relation between representation and evaluation of the design. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with a single design discipline.
Design loop 6 - Plaxis: as explained above. This system is also applied in the preferred situation to investigate solutions more in detail.	[1,1,2]	- Interact with the representation of the design. - Automate the relation between representation and evaluation of the design. - Store the final outcome of the design process, instead of the history of individual design operations. - Generate a design using a bottom-up method of generation; first the design elements, then the system. - Interact with data via objects. - Interact with a single design discipline.
Design loop 7 - a PDT system incorporating interdisciplinary input for geometrical drawings. An example of a possible system: a more extensive Subassembly Composer for which the algorithms describing the relations between design elements are automatically driven by input data from other disciplines.	[2,2,1]	- Interact with the representation of the design. - Automate interaction between different elements of the design representation. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with multiple design disciplines.
Design loop 8 - a PDT system automatically linking geometrical drawings with the cost estimates via volumes and quantities which result from these drawings.	[1,2,1]	- Automate interaction between different elements of the design representation. - Store the final outcome of the design process, instead of the history of individual design operations. - Generate a design using a bottom-up method of generation; first the design elements, then the system. - Interact with data via objects. - Interact with multiple design disciplines.
Design loop 8 - a PDT system with the purpose of equipment optimization. Examples of parameters: amount of equipment, distances, times and prices.	[2,1,3]	- Interact with generalised performance parameters of the design. - Automate the relation between performance parameters and the design representation. - Create multiple combinations of design representations quickly. - Store the history of the individual design operations, as well as the design outcome. - Generate a design using a top-down method of generation; first the system (procedures), then the design elements. - Interact with data via algorithms. - Interact with a single design discipline.

Appendix G: Results of the validation workshop

This appendix contains the additional insights gained from the validation workshop regarding enabler *standardisation in design elements and relations* and *interoperable and coherent data* for design loop 3 & 4.

Validation Session *Parametric Design Thinking* – Summary – 23/06/21

Attendants: General Manager (1x), Integral Design Manager (1x), Senior Cost Engineer (1x), Project Manager (1x), Geotechnical Engineer (1x) and Design Modeller (1x).

1. Standardisation in design elements and relations. The following design elements and relations in need for standardisation are identified for dike reinforcements:

- Up-to-date definitions of the earthwork planes (hectometre from/to axis).
- Working methods. Depending on the portability of the substrate, wet, dry or hydraulic, and phasing in work (large quantities in a short period or vice versa).
- Project strategy. For example a lot depends on the available time, such as settlement and phasing.
- Tender promises. For example environmental requirements or measures with regard to nuisance, these often already provide a strong framework of what can and cannot be done.
- Unit prices. For example fuel consumption. Fixing rates is difficult because you hire part of your equipment and part is our own inventory. There are also additional fees involved. Often a fixed and variable component, which can also differ per contract. Other prices that needs standardisation are prices for clay, sand, measures (drains/geotextiles), etc.
- Volumes. Focus is now too much on unit price, volume we take for granted, but that's where most of the pain comes from. Getting more reliability in volumes has a much bigger impact on price than unit prices.
- Quality of released soil (suitability). Not every material that is released can be applied to every place in the profile. Where you can use it depends on environmental conditions and lab tests. You have different types of inspection (e.g., erosion quality, water content). This needs to be accounted for in an interdisciplinary design system.
- Quantity per transport/volume per dumper. In practice you take less than you think per transport (as evidenced by experience and weighbridges). In practice, quantities are also often more than expected during the design. Divide hourly costs by dry volume. bulk factor.
- Distances. In practice we often drive differently than we think in advance. It is good to record the actually driven routes.
- Depot space. When do you return soil? How long do you want soil to wait in a depot and is there space available there? Taking up depot space also costs money.

2. Interoperable and coherent data. The following aspects in need for interoperable and coherent data are identified for dike reinforcements:

- Transparency. This is the key factor and applies to every discipline.
- Terminology between disciplines. This is mentioned as most important. An integrated look at naming. Cost codes for example do currently not match with the systems engineering terminology of modellers.
- Object Type Libraries: definitions of elements. Cross-sections can be a starting point. Different sections can be explored on standard and optional elements. The level of detail is herein important. Manufacturing tolerances can also be included in this analysis. Released soil is currently not or hardly included in an OTL, but are very important for dike reinforcements. The breakdown structure is not only about to be designed elements, but also released elements.

- Geo database accessible from different systems. FME can be used in order to create these integrations.
- Data regarding the existing situation (situation-zero). This must be correct and standard so that it is coherent for all projects. At the moment the data coming from a tender or a client varies. Agreements about this are useful so that you can ensure interoperable and coherent data.
- Standardisation in data transfers. This applies to all big data transfers (e.g., between modellers and cost-engineers). Superintendents also need to have a say in this. Agreements need to be made beforehand to ensure interoperability.
- 4D planning. For dike reinforcements this is especially interested with regard to a ‘soil-flow plan’.