Towards Flexibility in the Design and Management of Multifunctional Flood Defences

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What is flexibility and how to characterise and define it in the context of multifunctional flood defences ?

How to model the functional performance of a multifunctional flood defence in order to be used to devise strategies for maintaining the desired performance of the system under uncertainty ?

To what extent does an increase of the managerial flexibility improve the life cycle cost effectiveness of reinforcement of multifunctional flood defences ?

Towards Flexibility in the Design and Management of Multifunctional Flood Defences

Fatemeh (Flora) Anvarifar

Towards Flexibility in the Design and Management of Multifunctional Flood Defences

Fatemeh (Flora) Anvarifar

INVITATION

You are kindly invited to attend the public defence of my PhD dissertation

Towards Flexibility in the Design and Management of Multifunctional Flood Defences

Fatemeh (Flora) Anvarifar

Monday, September 25th, 2017 at 15:00

A brief introduction about this thesis will be given at 14:30

in the Aula of Delft University of Technology

WB

Propositions

accompanying the dissertation

Towards Flexibility in the Design and Management of Multifunctional Flood Defences

by

Fatemeh (Flora) Anvarifar

1. Risk management without addressing the emergent phenomena caused by interacting drivers of change creates a false sense of security.
2. The capability of rapid system reconfiguration is the most important factor to be addressed when planning to handle changes that cannot be anticipated.
3. It is not possible to precisely assess the value of flexibility under deep uncertainty. It is, however, possible to assess whether a system has a certain degree of flexibility.
4. The tradition of dike reinforcement in fixed (predetermined) time-steps does not provide sufficient flexibility to address the future needs.
5. Conducting collaborative research focused on resolving the challenges faced by the design and management of multifunctional flood defences requires sacrificing research autonomy.
6. To handle deep uncertainty, probabilistic thinking needs to be replaced by possibilistic thinking. (Modified from Marz et al., 2010)
7. While increasing system robustness may initially appear to provide more safety than increasing system flexibility, choosing for robustness will increase the chance of losing public trust in risk management over time.
8. PhDs should be awarded an advanced degree in conducting and, in particular, communicating research rather than becoming a Doctor (=teacher)
9. Improving the quality of research goes at the expense of the quality of the researcher’s personal life.
10. Google deserves credits for its significant contribution to contemporary PhD researches.

These propositions are regarded as opposable and defendable, and have been approved

as such by the promoters Prof. Chris Zevenbergen and Prof. Wil Thissen.

Towards Flexibility in the Design and Management of Multifunctional Flood Defences

Proefschrift

ter verkrijging van de graad van doctor

aan de Technische Universiteit Delft,

op gezag van de Rector Magnificus Prof. ir. K. C. A. M. Luyben,

voorzitter van het College voor Promoties,

in het openbaar te verdedigen

op maandag 25 september 2017 om 15:00 uur

door

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Master of Hydrology and Water Resources

IHE-DELFT Institute for Water Education (former UNESCO-IHE), The Netherlands

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In the memory of my mother who wished to see me achieving this milestone....

Summary

The very existence of the Netherlands and its prosperity is tightly linked and dependent on provision of sufficient and reliable flood protection. The risk of flooding is expected to rise as a result of various socio-economic developments and climatic changes. Whilst the densely populated urban areas need to be protected more than before, land scarcity creates competing development goals between flood protection and urbanism. Multifunctional use of flood defences has been proposed in the Netherlands to increase the synergy between flood protection and urbanism and to enhance the cost-effectiveness of flood protection.

In this research, a multifunctional flood defence represents a system of a flood defence (mainly a dike in this research) combined with one or more secondary functions. The structure of the secondary function should be partly or fully located in the flood protection zone. Flood protection zone refers to a reserved area around every flood defence, which can be used for future reinforcement. Such a multifunctional flood defence is aimed at fulfilling various societal functions such as housing, recreation and leisure, ecology, mobility in addition to flood protection.

Design and management of multifunctional flood defences is challenging and complicated. Once a multifunctional flood defence is constructed, it will become technically and financially hard to modify and adjust the system configuration. Such an infrastructure should maintain its desired performance although the system environment (physical, technical, political) evolves dynamically and steadily. In the presence of uncertainty about the future changes, successful design and management of multifunctional flood defences will require the capability to handle changing conditions. This research focuses on flexibility as a way of increasing the system capability to handle uncertain changes of future. The main objective of the research is thus to systematically explore different aspects related to incorporating flexibility in the design and management of multifunctional flood defences.

Multifunctional use of flood defences is an old tradition in the Netherlands. This research, first, explores the historical evolution of multifunctional flood defences in the Netherlands over the past century (Chapter 2). It appears that, in most cases, the usage of a specific area has gradually changed and evolved to become a multifunctional flood defence. The observations of land use change in four case studies including the flood defences of Vlaardingen and Vlissingen Cities, the Afsluitdijk and the Brouwersdam are used to reflect on the characteristics of the external dynamics instigating land use change as well the system response to change. The case study observations demonstrate that various drivers of change have interacted over a wide range of temporal and spatial scales resulting in the need for significant changes in the use of land. Almost in all cases the purpose of land use has changed to a domain that it was not previously conceived for. Furthermore, the presence and lack of flexibility in the system design has been a key factor in determining how to accommodate to the changing conditions and requirements.

Apart from the case studies, review of literature on handling uncertainty and change (Chapter 3) reveals that resilience; system robustness and flexibility are proposed as the three major attributes that can improve the system capability to handle future changes. It is observed that these three attributes have often been used interchangeably by scholars. Moreover, the proposed mechanisms to enable resilience, flexibility and robustness overlap and are not mutually exclusive. It is argued that among the three attributes, flexibility is the least rigorously investigated concept, in particular in the flood risk management literature. Furthermore, the review reveals that proper treatment of flexibility requires supplementary approaches. These can help the designers and decision makers to identify the options for increasing the system flexibility and to evaluate them. In doing so, three research objectives for treatment of flexibility for multifunctional flood defences are proposed that address the following research questions (Chapter 3):

1) What is flexibility and how to characterise and define it in the context of multifunctional flood defences?

2) How to model the functional performance of a multifunctional flood defence in order to be used to devise strategies for maintaining the desired performance of the system under uncertainty?

3) To what extent does an increase of the managerial flexibility improve the lifecycle cost-effectiveness of reinforcement of multifunctional flood defences?

The first question is answered (in Chapter 4) by proposing a framework in the form of four self-consistent and step-wise questions. Eight characteristic features are also distilled from literature to help answering each of these four questions. The names of the characteristic features associated with the four questions of the framework are bolded and underlined below.

(Q1) Why is flexibility needed?

- This question establishes the motivation for consideration of flexibility. This can be done by identifying the type of change (internal or external to the system) and uncertainty (e.g. sources, levels) that is chosen to be handled.

(Q2) What is it that flexibility is required for?

- This question seeks to describe the competences of flexibility to be specified as the goal of flexibility consideration (to handle the downsides or upsides of uncertainty) and the capabilities of flexibility to achieve its goal (via time, performance, cost penalties prevented).

(Q3) What are the dimensions of flexibility?

- This question indicates the extent to which flexibility can be achieved, from a temporal point of view (strategic/tactical/operational) and the mode of response (proactive/reactive).

(Q4) What needs to change or be adapted?

- This question discusses the potential ways of achieving flexibility. In this research, flexibility types (or managerial flexibility) indicate the managerial actions and decisions that should be taken to consider and use flexibility while flexibility enablers (or design flexibility) refer to the sources of flexibility (or where flexibility is) embedded in the system's technical design.

Subsequently, the working definition of flexibility is developed as 'a multifunctional flood defence system attribute that enables responding to changing conditions, in order to reduce the negative consequences, and to exploit the positive upsides of uncertainty and change, in a performance-efficient, timely and cost-effective way.'

The framework is applied in an illustrative case study. It is shown that affective flexibility consideration for a multifunctional flood defence system requires consideration of the mutual impacts of the system functions on each other. It is concluded that the iterative use of the framework can enhance the clarity about the concept of flexibility and can serve as a

guideline for structuring the discussion of flexibility and for identifying the sources of flexibility in the design and management of multifunctional flood defences.

The second question of the research is answered (in Chapter 5) by proposing a framework for performance analysis of multifunctional flood defences. The framework is based on ‘Functional Resonance Analysis Method’ (FRAM), which has originally been developed for retrospective safety analysis in aviation. With the use of the proposed framework, first, the functional components of a multifunctional flood defence are characterised and visualised. Thereafter, scenario-based potential dependencies between the functional components of the multifunctional flood defence under consideration (with specific intended dependencies) are identified and illustrated. The identified potential dependencies are then used to devise strategies to prevent, control, or mitigate the negative impacts or to amplify the positive impacts of these potential dependencies.

The performance analysis method is applied to compare four alternative designs of a multifunctional flood defence, based upon the case of Katwijk. A scenario of an extreme event is developed to investigate whether the potential dependencies between the functional components of each alternative design can impact the flood protection function. The analysis results demonstrate that the secondary function may impact the flood protection function both positively and negatively. These interactions, and particularly the positive impacts of the secondary function on the flood protection function, have not been explicitly considered in the design phase. The proposed performance analysis method is found to be useful to facilitate the process of identifying and assessing the options for increasing the system’s flexibility. This customised framework can serve as a useful complement to reliability analysis methods for enriching the performance analysis of multifunctional flood defences.

To answer the third question of the research, a cost-effectiveness analysis is carried out in Chapter 6. It is explored whether increasing the managerial flexibility embedded in reinforcement strategies would be advantageous in the context of multifunctional flood defences. A cost-effectiveness analysis is conducted to compare the lifecycle costs of two flexible strategies against a baseline strategy in two scenarios of sea level rise. Flexibility manifests itself in the allocation of the design lifetime (fixed/variable & short/long) of the reinforcement strategies. The strategies are examined in eight case studies, two different scenarios of sea level rise, and for four discount rates.

The results show that flexible strategies have the potential to significantly reduce the lifecycle costs of reinforcement, in particular for monofunctional flood defences. While it seems to be always advantageous to stage the dike reinforcement for monofunctional dikes, care should be taken in assuming that staged development of dikes is also a preferred strategy for multifunctional dikes, especially when the ratio of fixed over variable costs (f/v) is high. It is seen that the cost effectiveness of the strategies is sensitive to the underlying assumptions regarding the extent of sea level rise and the discount rate. Therefore the use of only one scenario for developing and evaluating the reinforcement strategies is strongly discouraged. Furthermore, the results demonstrate that the other developments around the dike need to be explicitly addressed in the evaluation of reinforcement strategies. It is argued that the current engineering practice can be improved if the possibility of a variable design lifetime is also included in reinforcement decision making.

The main conclusion of research is that increasing flexibility in the design and management of multifunctional flood defence can indeed be useful to accommodate future changes more effectively. This is mainly because of the enabled possibility of constant learning as well as the possibility to adjust the course of action. Furthermore, flexibility can be aimed at not only handling the negative downsides of uncertainty, but also taking advantage of future opportunities. Therefore, the use of flexibility can also result in more efficient use of the available resources.

Furthermore, it is concluded that multifunctional use of flood defences does not necessarily reduce the level of safety provided by the flood defence. A tight link between the functions of a multifunctional flood defence can, in some cases, even improve the performance of the flood protection function. Moreover, the secondary function of a multifunctional flood defence can be designed in such a way as to contribute to increasing flexibility in the design and management of the flood defence. Although the initial cost of constructing such a secondary function might be higher, the need for a lower dike and the reduced cost of future reinforcement can arguably compensate this extra initial cost.

Samenvatting

Nederland dankt haar bestaan en welvaart aan een uitgebreid systeem van waterkeringen dat een betrouwbare hoogwaterbescherming biedt. Het risico van overstromingen zal naar verwachting stijgen als gevolg van socio-economische ontwikkelingen en klimaat verandering. Vooral voor de dichtbevolkte, verstedelijkte gebieden zal het beschermingsniveau daardoor moeten toenemen. De ruimteclaims die het versterken van dijken met zich meebrengen, zullen moeten concurreren met andere ruimteclaims voor o.a. stedelijke uitbreiding. Multifunctioneel gebruik van waterkeringen is in Nederland al enige tijd geleden geïntroduceerd met als doel om de ruimte die nodig is voor hoogwaterbescherming en voor verstedelijking te combineren. Op deze wijze kan de kosteneffectiviteit van hoogwaterbescherming worden verhoogd.

In dit onderzoek wordt onder een multifunctionele kering verstaan een kering die gecombineerd is met (een) andere functie(s). Het ruimtebeslag van de secondaire functie dient in zijn geheel of gedeeltelijk samen te vallen met de zone langs (binnen- en buitendijkse ruimte) de kering. Deze zone, aangeduid met de *waterkeringszone*, dient voldoende ruimte te bieden voor eventuele toekomstige uitbreiding. Een multifunctionele kering heeft als doelstelling om naast de primaire functie van waterkeren ook één of meerdere maatschappelijke functies te vervullen als woningbouw, recreatie, ecologie en mobiliteit.

Het ontwerp en beheer van multifunctionele keringen is uitdagend en complex. Wanneer een multifunctionele kering eenmaal ontworpen en gebouwd is, zal het technisch en financieel lastig zijn aanpassingen in het ontwerp aan te brengen. Het ontwerp van een dergelijk infrastructureel werk zal ook bij veranderende omgevingscondities (fysisch, technisch en politiek) in de toekomst voldoende veiligheid moeten kunnen bieden. Dit onderzoek richt zich op flexibiliteit als systeemeigenschap om met toekomstige onzekerheden om te gaan. De belangrijkste doelstelling van het onderzoek is om de verschillende aspecten van flexibiliteit in het ontwerp en beheer van multifunctionele keringen systematisch in beeld te brengen.

Multifunctioneel gebruik van keringen is een oude traditie in Nederland. Dit onderzoek zal eerst de historische ontwikkelingen van multifunctionele keringen in Nederland over de afgelopen eeuw schetsen (Hoofdstuk 2) aan de hand van voorbeelden (case studies). Hieruit

blijkt dat bij de onderzochte voorbeelden de functie van de *waterkeringszone* door de tijd heen geleidelijk veranderd is en 'multifunctioneel' geworden is. Deze voorbeelden betreffen de hoogwaterkering bij Vlaardingen en Vlissingen, de Afsluitdijk en de Brouwersdam. Uit de onderzochte voorbeelden blijkt dat onder invloed van verschillende factoren ('drivers of change') het landgebruik van de waterkeringszone in de tijd aanzienlijk is veranderd en dat vooraf bij het ontwerp hier geen rekening mee gehouden is. Bovendien heeft de mate van flexibiliteit in het ontwerp een grote rol gespeeld bij de wijze waarop de waterkeringen zijn aangepast (en dus multifunctioneel zijn gemaakt) aan de veranderende condities en eisen.

Uit een bestudering van de literatuur over het omgaan met onzekerheden en veranderingen (Hoofdstuk 3) is gebleken dat veerkracht ('resilience'), systeem robuustheid, en flexibiliteit aangehaald worden als de drie belangrijkste attributen die het vermogen van een systeem weergeeft om zich aan te kunnen passen aan veranderende omstandigheden. Vervolgens is geconstateerd dat de begrippen resilience, flexibiliteit en robuustheid elkaar overlappen. Het blijkt dat van de drie attributen, flexibiliteit het minst goed onderzocht is in de wetenschappelijke literatuur, in het bijzonder in de literatuur over hoogwaterbescherming. Tenslotte is vastgesteld dat voor het identificeren en waarderen van flexibiliteit nieuwe, aanvullende raamwerken nodig zijn. Gebaseerd op de bevindingen van het literatuuronderzoek en de case studies over de historische ontwikkeling van multifunctionele keringen zijn drie onderzoeksvragen geformuleerd. Deze onderzoeksvragen zijn:

1) Wat is flexibiliteit en hoe kan deze worden gekarakteriseerd in de context van multifunctionele keringen?

2) Hoe kan de functionele performance (prestaties) van een multifunctionele kering worden gemodelleerd en in hoeverre kunnen de uitkomsten hiervan een rol spelen bij het ontwikkelen van strategieën voor sturing op de gewenste performance met in achtneming van alle onzekerheden over lange termijn veranderingen?

3) In welke mate kan de 'managerial' flexibiliteit worden ingezet om de kosteneffectiviteit voor de gehele levenscyclus van multifunctionele keringen te vergroten?

De eerste onderzoeksvraag is beantwoord (in hoofdstuk 4) door een raamwerk te presenteren, waarbij stapsgewijs een *viertal vragen* wordt gesteld. Bij de ontwikkeling van dit raamwerk zijn acht karakteristieke kenmerken gebruikt die op basis van het literatuuronderzoek zijn geïdentificeerd. Deze kenmerken zijn hieronder, bij de beschrijving van de viertal vragen, vetgedrukt weergegeven.

(vraag 1) Waarom is flexibiliteit nodig? Deze vraag gaat over de feitelijke motivatie van het gebruik van flexibiliteit. Deze kan worden vastgesteld door het type **verandering** (intern of extern van het systeem) en door de mate van **onzekerheid** (bijv. herkomst, niveau) van deze verandering te kennen.

(vraag 2)) Waar is flexibiliteit voor nodig? Deze vraag beoogt het doel van flexibiliteit te beantwoorden (c.q. hoe om te gaan met zowel de voor- als nadelen van onzekerheid), alsmede de mogelijkheden die flexibiliteit biedt om dit doel te bereiken.

(vraag 3) Wat zijn de dimensies van flexibiliteit? Deze vraag geeft inzicht in de mate waarin flexibiliteit kan worden bereikt gezien vanuit het perspectief van **de temporele dimensie** (vanuit strategisch/tactisch/operationeel oogpunt) en in de manier (**'wijze van respons'**) waarop dit kan worden bewerkstelligd (c.q. proactief/reactief).

(vraag 4) Wat vraagt om aanpassing en/of verandering? Deze vraag zoekt naar mogelijke manieren om flexibiliteit te in te bouwen dan wel te vergroten. In dit onderzoek geven de verschillende vormen ('**types**') van flexibiliteit de *management acties* en beslissingen weer, die nodig zijn om deze te beïnvloeden/te vergroten, terwijl de '**enablers**' van flexibiliteit verwijzen naar de mogelijkheden die het *technisch ontwerp* van het systeem zelve biedt om flexibiliteit in te bouwen dan wel te beïnvloeden.

Vervolgens is een werkdefinitie voor flexibiliteit ontwikkeld. Deze luidt: "een multifunctionele kering is een kering, die in staat is om zich tijdig en op een kosteneffectieve manier aan te passen aan veranderende omstandigheden op een zodanige wijze dat de negatieve gevolgen van deze veranderingen zoveel mogelijk beperkt blijven en de positieve gevolgen daarvan maximaal benut worden."

Om het raamwerk te toetsen is het toegepast op een case studie. Hieruit is gebleken dat voor een effectieve beschouwing van flexibiliteit bij multifunctionele keringen het vereist is de wederzijdse beïnvloeding van de verschillende functies van het systeem (c.q. multifunctionele kering) te kennen. Voorts is gebleken dat het iteratief gebruik van het raamwerk helderheid verschaft over het concept flexibiliteit. Het kan dienen als een richtlijn voor het structureren van de onderliggende vragen, die bij het ontwerp en management van flexibiliteit een rol kunnen spelen en ook biedt het ondersteuning bij het identificeren van mogelijkheden om de flexibiliteit in het ontwerp en management te beïnvloeden.

De tweede onderzoeksvraag beoogt (hoofdstuk 5) een raamwerk te presenteren voor het analyseren van de prestaties ('performance') van multifunctionele keringen. Het raamwerk is gebaseerd op de zogenaamde "*Functional Resonance Analysis Method*" (FRAM), die oorspronkelijk ontwikkeld is voor veiligheidanalyses in de luchtvaart. Dit raamwerk heeft als doelstelling de functionele componenten te modelleren en te visualiseren waardoor meer inzicht wordt verkregen in hun beoogde en mogelijke wederzijdse afhankelijkheid zowel voor wat betreft de positieve als negatieve gevolgen daarvan.

Het raamwerk is toegepast om vier alternatieve ontwerpen van een multifunctionele kering met elkaar te vergelijken. Deze alternatieven zijn gebaseerd op de case studie Katwijk. Een scenario waarbij sprake is van een extreme storm is uitgewerkt om te onderzoeken of de potentiele afhankelijkheden tussen de functionele componenten van de verschillende alternatieve ontwerpen een positieve dan wel negatieve invloed hebben op de mate waarin bescherming tegen hoogwater wordt geboden. De resultaten van de analyse laten zien dat de toevoeging van een extra functie in de nabije omgeving van de kering, een positieve danwel negatieve invloed kan hebben op de hoogwater beschermende functie van de kering. De invloed en dus ook de positieve effecten van een extra functie zijn echter niet meegenomen in de ontwerpfase van project. Uit dit onderzoek is gebleken dat het voorgestelde raamwerk handreikingen biedt bij het identificeren en bepalen van de mogelijkheden om de flexibiliteit van het system (c.q. de multifunctionele kering) te vergroten. Dit ontwikkelde raamwerk kan een nuttige aanvulling zijn op de technische beoordelingsmethoden (betrouwbaarheidsanalyse) van multifunctionele keringen.

Om de derde onderzoeksvraag (hoofdstuk 6) te kunnen beantwoorden is een kosteneffectiviteitsanalyse uitgevoerd. Onderzocht is in hoeverre een toename van de flexibiliteit in het beheer (als onderdeel van een dijkversterkingsstrategie) voordelen zou kunnen opleveren voor multifunctionele keringen. Voor de kosteneffectiviteitsanalyse zijn de 'lifecycle costs' van twee flexibele strategieën vergeleken met die van een baseline strategie voor twee scenario's van zeespiegelstijging. Flexibiliteit komt tot uitdrukking in de ontwerplevensduur (vast/variabel en kort/lang) van de dijkvesterkingsstrategie. De strategieën zijn onderzocht voor acht case studies, twee verschillende scenario's van zeespiegelstijging en voor vier waarden van de discontovoet.

De resultaten laten zien dat flexibele strategieën het vermogen hebben om de levencycluskosten van dijkverzwaring drastisch te verlagen. Dit geldt in het bijzonder voor monofunctionele keringen. Hierbij zij opgemerkt dat enige voorzichtigheid geboden is om aan te nemen dat een trapsgewijze opwaardering van dijken ook een voorkeurstrategie is voor multifunctionele dijken, vooral wanneer de verhouding vaste versus variabel kosten hoog is. Het is gebleken dat de kosteneffectiviteit van de strategieën gevoelig zijn voor de onderliggende aannames omtrent de keuze van de ontwerp-levensduur en de mate van zeespiegelstijging en de discontovoet, alsook van het niveau van ontwikkeling achter de dijk. Het gebruik van één scenario voor de ontwikkeling en evaluatie van een dijkversterking strategie wordt daarom ontraden. De resultaten laten ook zien dat andere ontwikkelingen rond dijktracés expliciet meegenomen moeten worden bij de evaluatie van dijkversterkingsstrategien. Tenslotte is beargumenteerd dat de huidige ingenieurspraktijk verbeterd kan worden, indien de mogelijkheid van een variabele ontwerplevensduur wordt meegenomen in het besluitvormingsproces van dijkversterking.

De belangrijkste conclusie van dit proefschrift is dat een toename van de flexibiliteit in het ontwerp en beheer van multifunctionele keringen inderdaad bij kan dragen aan het vergroten van de effectiviteit om te kunnen inspelen op toekomstige veranderingen. Dit is met name een gevolg van het feit dat het leren vermogen toeneemt en omdat de mogelijkheid om bij te sturen ook vergroot wordt. Bovendien schept flexibiliteit de mogelijkheid om niet alleen de negatieve gevolgen van onzekere veranderingen te kunnen beperken, maar ook om te profiteren van de positieve veranderingen die zich voor kunnen doen. Om deze reden kan het gebruik van flexibiliteit leiden tot een meer efficiënt gebruik van de beschikbare middelen.

Tenslotte is in dit onderzoek geconcludeerd dat multifunctioneel gebruik van keringen niet noodzakelijkerwijs leidt tot een verhoging van het veiligheidsniveau. Door de synergie tussen verschillende functies/onderdelen van een multifunctionele kering kunnen in sommige gevallen, de prestaties van de hoogwaterbeschermende functie verbeterd worden. Bovendien kan het ontwerp van een secondaire functie van een multifunctionele kering een bijdrage leveren aan de verhoging van de flexibiliteit van het ontwerp en beheer van de kering als geheel. Ofschoon de initiële kosten van de aanleg van een multifunctionele kering hoger kunnen zijn (dan die voor een monofunctionele kering) door de kosten voor de secondaire functie, kunnen deze gecompenseerd worden door een besparing op de kosten van toekomstige dijkversterking.

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1 Introduction

"Change alone is eternal, perpetual, immortal"

Arthur Schopenhauer, German Philosopher

1.1 Background

Worldwide the number of people threatened by flooding has increased significantly (Butt et al., 2015, Adelekan, 2015, Yang et al., 2015, Papagiannaki et al., 2017). This trend is more visible in delta regions, where intense urbanization, growing population and climatic changes (e.g. sea level rise) are among the factors that contribute to an increasing risk of flooding (Tessler et al., 2015, Rosenzweig et al., 2011). It is estimated that up to 150 million people and US $35 trillion of assets will be affected by climate change by 2070 (Nicholls et al., 2007). According to the Organisation for Economic Cooperation and Development (OECD), a quarter of the large delta cities around the world will need better flood protection to combat sea level rise (Hallegatte et al., 2013). The World Bank estimates that the costs of flood damage to large coastal cities could rise to $1 trillion a year if cities do not take steps to adapt (World Bank, 2013).

Since existing flood defences worldwide have been designed for past conditions, a large proportion of the flood defences are aging and need to be replaced and/or improved at a cost estimated around US $50 billion per year for the major delta cities in the world (Hallegatte et al., 2013). While reducing flood damage in the future is expected to be capital extensive, it might be possible to make use of the struggle against rising sea levels in coastal areas as an opportunity to boost societal and economic growth (Kabat et al., 2009). Through innovative solutions, the increasing risk of flooding may not solely be regarded as something purely negative causing financial burden (Wesselink, 2007, Bijker, 2009). Rather, as also proposed by the Dutch Delta Committee, climate change can be the engine for coastal regions, in this case in the Netherlands, to move into a sustainable future (Uittenbroek et al., 2013, Offermans et al., 2013, Ligtvoet et al., 2015).

One of the innovative solutions proposed in the Netherlands is to make use of the limited available land not only to improve flood protection but also to provide other non-water-retaining functions (Aerts et al., 2013a, Stalenberg, 2010). The combined development is called a multifunctional flood defence and is expected to be a functional part of its rural or urban environment. Such a development is aimed at fulfilling various societal functions such as housing, recreation and leisure, ecology, mobility and transport, and the like (Vrijling et al., 2012). It is expected that the multifunctional use of flood defences has the potential to increase societal 'added value' (Van Alphen, 2015) by mutually reinforcing the goals of the system functions (Heijden and Bakker, 2016) as well as by increasing the cost-effectiveness of flood protection (Van Loon-Steensma and Vellinga, 2014, Aerts, 2016, Stalenberg, 2010).

1.2 Research problem and main objective

The design and management of multifunctional flood defences is a complicated and challenging task. This is because of a wide range of considerations that must be taken into account (Farrell et al., 2015, Vrijling et al., 2012). As a critical infrastructure, such structures are required to be always available, highly reliable, and easily maintainable (Ajah, 2009). The environment (physical, technical, political) in which a multifunctional flood defence works, however, evolves dynamically and steadily. While the configuration of a multifunctional flood defence is determined at the present time, it is very possible that future requirements will be outside the range of initial estimates. Therefore, successful design and management of multifunctional flood defences in a dynamic contemporary environment need to not only address today's need but also to accommodate tomorrow's requirements.

Typically, a multifunctional flood defence represents a physical structure that is capital extensive to develop and difficult to modify. Failing to address the possibility that the system might need modification after it has been constructed may lead to rigid system configurations that cannot accommodate future requirements properly. At the present time, knowledge about change instigators (driving forces), processes (mechanisms) and consequences is still incomplete (Ross et al., 2008, Straub and Špačková, 2017, Von der Tann et al., 2016). In the presence of uncertainty about future changes, the main challenge in this research is how to enhance the capability of multifunctional flood defences to maintain their desired performance under changing conditions.

The literature on coping with uncertainty in the design and management of critical infrastructure is growing steadily. The premise of the proposed approaches to handling uncertainty is to improve the system capability to accommodate the changing circumstances (Hallegatte et al., 2012, Hamarat et al., 2013, Park et al., 2013, Chang, 2014, Babovic, 2014, Gil and Biesek, 2014). One of the key attributes that is proposed as a critical system quality to handle uncertainty and change is flexibility (Walker et al., 2013, Linquiti and Vonortas, 2012, Thissen, 2012). Similarly, it is chosen in this research to address uncertainty by considering flexibility. The main objective of this research is thus to systematically explore different aspects related to incorporating flexibility in the design and management of multifunctional flood defences.

1.3 Research approach

In order to achieve the main objective of the research, the research presented in this dissertation consists of three principal parts:

First, the dissertation starts by providing some background information that shapes the main objective of the research as presented in the preceding section. Subsequently, Chapter 2 presents case studies of the evolution of four multifunctional flood defences in the past century. This is followed by a review of the literature on handling uncertainty in Chapter 3. The case study findings and the outcome of the literature review are then used to frame the three specific objectives and questions of this dissertation as presented at the end of Chapter 3.

The second part of the dissertation is presented in Chapters 4, 5 & 6, which each address one of the specific objectives of the research. In the third part of the dissertation, answers to the research questions and a discussion of the results are given in Chapter 7, and some suggestions for the way forward are made in Chapter 8. Figure 1 sketches the outline of the dissertation which will be further explained in Chapter 3.

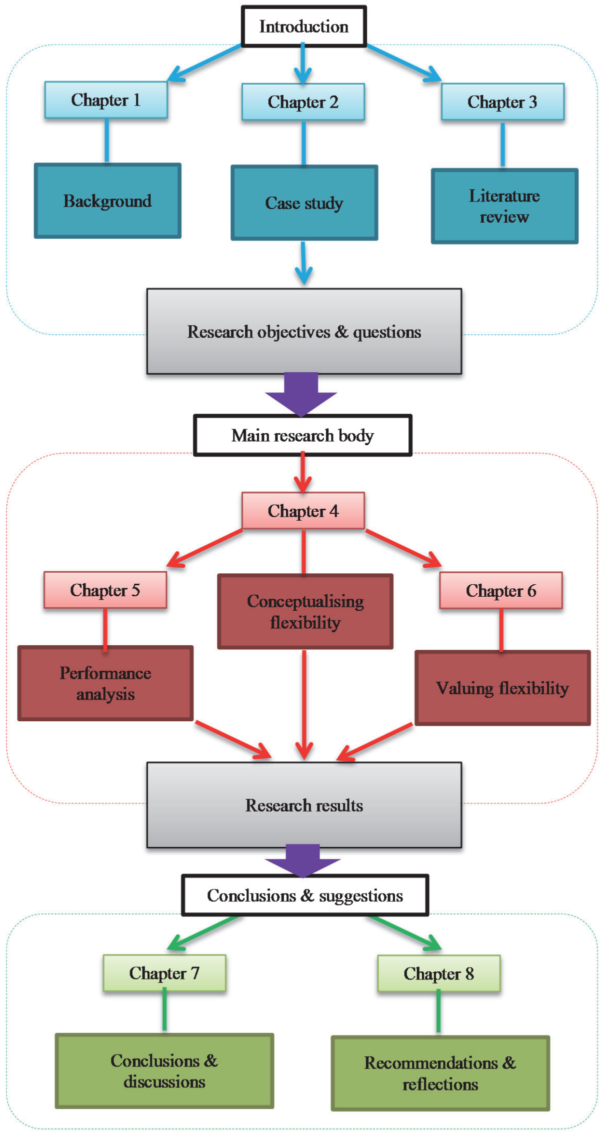

Figure 1, the dissertation outline

2 Looking back to look forward: case studies

"Experience is the mother of science."

Anonymous

Collected in Henery George Bohn, A Handbook of Proverbs: Comprising Ray's Collection of English Proverbs (1855), 352.
Science quotes on: | Experience (171) | Science (1133)

2.1 Background: the Dutch flood management practice in time

The Netherlands is a delta country that can be considered as a water gateway. Where the rivers discharge the melt water from the Alps to the North Sea, the rainwater makes its way to the sea both overland and underground. The geographical location of the country makes it very vulnerable to both sea and river flooding. The whole country is currently protected against coastal and river flooding by 3,500km of primary flood defences accompanied by 14,000km of secondary flood defences around the basins, polders and canals. Additionally, an extensive and complex system of ditches, waterways and pumping stations serve to manage the groundwater levels and drain the rain water in the polders. This sophisticated flood management system has not come to existence in one night.

The earliest known evidence of damming against flooding in the Netherlands dates back over 2000 years to the late Iron Age (De Ridder, 1999). However, it was in the early Middle Ages that, after the departure of the Romans, a growing population created settlements in the low-lying marshlands. The need for grazing pastures for livestock led to the damming of streams and construction of low dikes. The combined effects of soil subsidence and rising sea levels meant this population undertook to control flooding by constructing closed dike systems along the major rivers during the 13^{th} century. The continuous economic growth and rising population required large-scale hydraulic engineering works such as land reclamation, polders and large-scale peat extraction. However, the appearance of naval shipworm around 1730 caused the disintegration of many wooden structures along the coast, including breakwaters and dikes. This disaster switched practice towards the construction of less steep dike structures with stone revetments until the 19^{th} century. From 1900 onwards, advances in science, technology, transportation and mass production of materials such as concrete enabled new hydraulic works on a large scale, such as the closing of the Zuiderzee and the ambitious Delta Works in reaction respectively to two serious floods in 1916 and 1953 (Tol and Langen, 2000, Orr et al., 2007, Kuster, 2008).

The presence of the flood defences has significantly reduced the likelihood of flooding in the Netherlands. The improved flood safety level has resulted in extensive economic developments and dramatic land use change in the low land areas. For instance, port developments and advancements in shipping industry have attracted more and more people to live in the coastal lowlands. Gradually, the transformation of economy from rural to industrial has resulted in shaping densely populated urban areas, in particular in the marshlands with relatively lower elevations. In these lowland regions, draining the peat lands and digging canals and water ways has continuously lowered the average peat-lands elevation to approximately 3m under mean sea level comparing to its previous 3m above sea level a thousand years ago. Due to the increasing developments in these areas, the relative depth and damage of any potential flooding is expected to become larger and larger in time.

Prosperity of the Netherlands can only continue durably and steadily if protection against flooding continues properly and pro-actively. Although only a very rare extreme event can cause the current flood defences of the Netherlands to fail, any such failure can result in inconceivable socio-economic damages that can disrupt the entire country. Since the level of safety provided by the flood defences deteriorates progressively, maintaining sufficient flood protection will require continuous maintenance and development of flood defences.

Often, flood defence improvement needs extra space to be allocated to the widening and or heightening of such a structure. In practice, the intensive economic development and urbanization in the low land regions has taken the limited land available resulting in land scarcity. This land scarcity creates conflict between the development and reinforcement of the flood defences and urban developments. On the one hand, the increasing exposure and vulnerability in the urban areas requires further expansion of the flood defences. One the other hand, it is expected that flood defence development should not hamper the function of urban structures visually and physically, but should contribute to spatial quality of the area. In face of land scarcity and competing development priorities, shared use of the land via multifunctional use of flood defences has been proposed as a promising solution for balancing these different needs (Stalenberg, 2010).

Multiple use of land for flood protection and other purposes in the Netherlands is however as old as the defences themselves. The difficulties of maintaining and assessing flood defences have gradually caused the laws and regulations for building on flood defences to be tightened. Today, the need for resource efficiency strongly supports the idea of multifunctional use of flood defences. Both the design and management of multifunctional flood defences are challenged by the limited knowledge and uncertainty about the past, current and future factors that may greatly influence the functioning and existence of these infrastructures. Given the extent of capital costs required for the development of multifunctional flood defences and the irreversibility of these interventions, successful design and development of multifunctional flood defences require addressing the ways of handling the dynamics impacting their performance. To do so, exploring the factors that have shaped the evolution of multifunctional flood defences in the past can be very useful to broaden the knowledge of-, and to prepare for what may happen in the future.

In this regard, the next section presents a chronological overview of the changes in land use in four case studies. Since the area under consideration in each case study has gradually evolved to become a multifunctional flood defence; the focus of the overview is to explore the dynamics that have driven the change in the use of the land resulting in presence of current multifunctional flood defences. The case study findings are presented in terms of characteristics of the external dynamics (driving forces) that have caused significant changes in the land use and the system characteristics that have impacted its response to these externally initiated changes.

2.2 Evolution of multifunctional flood defences: four case studies

In this research, a multifunctional flood defence indicates a zone that is primarily used for flood protection, but serves other non-water retaining functions (e.g. transportation, housing).

Traditionally, every flood defence in the Netherland has a flood protection zone around it. This zone refers to a reserved area around the flood defence (or the flood protection zone) that offer restrictions in the use of the land on the sides of a flood defence (TAW, 1998). In this research, the structure of the secondary function(s) of a multifunctional flood defence must be fully or partly located in the flood protection zone of the flood defence under consideration.

Generally speaking, a flood defence may also comprises of dikes, flood walls, pumping stations, gates closure structures, natural features, and other associated structures. The term 'flood defence' is mostly used in this research to refer to a 'dike'. Following the description presented in CIRIA (2013), a dike presents a predominantly earth, structures constructed for the purpose of water retaining.

The term system is often used in this research to refer to a multifunctional flood defence. Using the definition of system as appeared in the INCOSE handbook (Haskins et al., 2006), the term 'system' is defined as a '*combination of interacting components organized to achieve one or more stated purposes*.' Here in this research, whenever the term system is applied, it refers to the combination of technical & functional components of a multifunctional flood defence as well as the local actors involved in decision making on development and maintenance of the whole structure.

The case study of this chapter is aimed at elaborating on the characteristics of the external dynamics, which have shaped the future of multifunctional flood defences over the past century, and to explore the factors affecting the response of the system to these changes. The system response implies for how the use of land has been significantly re-shaped or re-constructed after the occurrence of the external changes. Herein, the land use is characterised by the 'arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it' (FAO, 1999). The dynamics under consideration in this section refer to the external factors that have influenced the land use change, and are called the 'driving forces' or 'drivers of change'.

The European Environment Agency (EEA) defines a driver of change as a need, which can vary from the needs of individuals for shelter, food and water to low cost profitability and to productivity in industrial sectors (Kristensen, 2004). The Millennium Ecosystem Assessment defines a driver as 'any natural or human-induced factor that directly or indirectly causes a change in an ecosystem'. A direct driver refers to explicit causes of change that can be identified and measured. An indirect driver has a secondary impact by altering one or more of impacts of direct drivers (Leemans et al., 2003). In this section, a driver of change refers to a natural or human induced process (Bürgi et al., 2004) that that has resulted in tangible land use changes in the case studies. The land use change refers to major visible adjustments in the function, size, and existence of a multifunctional flood defence over time.

As it will be seen in the cases, the combined use of an area for flood protection and other purposes had not necessarily been planned in advance. There are actually very limited cases in which the decision makers had the initial intention to develop such an integrated infrastructure. Accordingly, the case studies of are divided into two types that are named here as 'evolved' and 'planned' multifunctional flood defences. An 'evolved' multifunctional flood defence refers to a specific area that was initially constructed to operate one function, but evolved to have a flood protection and some additional functions. On the other hand, a 'planned' multifunctional flood defence refers to the situation in which the intention of multiple use of the land had been embedded in the development plan from the beginning.

The chronological review begins with describing the land use in each case as early as in 1900, when the considered sites had not yet been used for multiple purposes. It is acknowledged that thorough analysis of the drivers of change requires deep understanding of various dependencies, interactions, and feedback loops involved in the change process at several temporal and spatial scales (Allen, 1987). The analysis of this research is, however, limited to the identification of the major drivers of land use change that can be inferred from the available historical documents (in Dutch and English), the websites of the municipalities, and a limited number of relevant papers.

2.2.1 Vlaardingen: an evolved multifunctional case

Vlaardingen is a small city in the South of the Netherlands (Figure 2). It locates on the North bank of the River Meuse, which is a tidal river under influence of the North Sea. The city centre is currently protected by a multifunctional flood defence consisting of a rail road, an embankment, and several culverts passing under the structure. The Vlaardingen railway is a part of a national railway network. The case study addressed in this section only refers to the part that is lying along the riverfront of Vlaardingen and is a part of the flood protection scheme of the city. The historical information of this case study is extracted from the following sources: (Chabinath et al., 1995, De Ridder, 1999, 1916, 1910, Anonymus, 1895, Brouwer et al., 2012, Van Roosmalen and Van Gessel, 2012, Gemeente-Midden-Delfland, 2010, Vehgan, 2016).

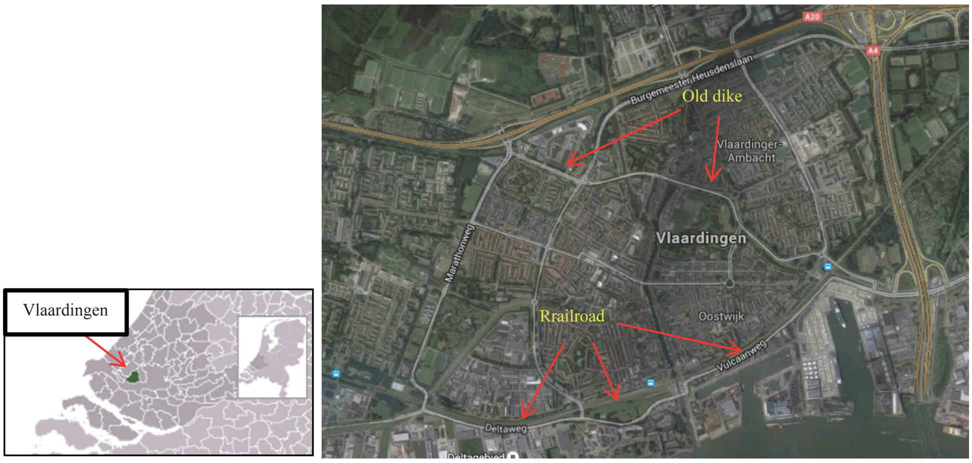

Figure 2, the multifunctional flood defence (the railway) in the city of Vlaardingen (modified from Google Maps)

In the beginning of the 20th century, Vlaardingen was protected against flooding by an old dam passing through the middle of the city (from the 12th century), two discharge channels, a system of rich breakwaters, and shorter summer dikes protecting the newly developed harbour areas. The south side of the city was disconnected from the river via a railway constructed on an embankment in 1886-1893. It was elevated to facilitate water crossing under the railway and because the ground soil was soft and swampy. At the crossing of the railway and the harbour channel a (mobile) bridge and a safety lock were built. This lock was designed only to be closed during high storm surges in the tidal river to prevent flooding of the harbour area. After the construction of the railway, in 1895 a new port was dredged to the south of the railway (the ‘Koningin Wilhelminahaven’) and a new housing area was constructed between the old sea dike and the railway near the new harbour.

In 1916 a large flood occurred in the northern part of the Netherlands. As a reaction the local water board of the area decided to improve the old dike which protected the old district of the city. This involved removal of several houses, warehouses and public buildings along the existing dike, which is currently located underneath the Hoogstraat in Vlaardingen. Due to the difficulties in reinforcing this hidden dike, the municipality of Vlaardingen suggested to the local water board to make use of the railway embankment to build a new sea dike and a (double) safety lock in the harbour channel, including a new rail bridge. This solution was attractive since it could also protect the newly expanded areas of Vlaardingen outside the existing dike. As a result, the river side of the railway embankment was heightened and covered by grass resulting in a multifunctional structure. Additionally, a new bridge and discharge sluices were also constructed by the municipality of Vlaardingen to facilitate the discharge of surface water to the river.

In the period until 1950 the city centre grew on the both sides of the railway. While the area between the old dike and the railway was used for housing, the area between the railway and the river was developed as an industrial area. During the storm surge of 1953, the river water rose to just below the crest level of the railway embankment. Although the city remained safe from flooding, the embankment, which had a sandy core body, allowed seepage from its inner side. Due to the lack of any serious damage, the dike improvement did not receive a high priority in the national Delta Works programme after the 1953 flooding.

In 1995 the dike was improved and raised to meet present day standards. Currently, in addition to its role in flood protection, the dike also acts as a green zone separating the housing area to the north of the railway and the industrial area to the south. The old city dike is only visible under a grass cover in some areas and has lost its initial function.

Currently the city is threatened by groundwater flooding due to the high level of subsidence. However, the existing culverts, passing underneath the multifunctional flood defence, and the ditches along the railway, running on either side of the central station, have been sufficient to keep the city dry. There is a need for improving the urban drainage system of the city to discharge the extra surface water. A further consideration is that the railway embankment is required to meet current safety standards that are conditional upon the existence of the Maeslantkering Barrier in Rotterdam. It can be expected that any change in the state of this storm surge barrier (e.g. if it is removed) may require extra measures to provide sufficient safety and to compensate changes to the railway.

2.2.2 Brouwersdam: an evolved multifunctional case

The Brouwersdam is a closure in the South west of the Netherlands (Figure 3), connecting the former islands of Goeree-Overflakkee and Schouwen-Duiveland. The dam has closed the former Rhine-Meuse estuary on the border of two provinces of South Holland and Zeeland, creating the Lake Grevelingen. This region represents a multifunctional area that is used for flood protection and water sports on the North See side (e.g. wind surfing, sailing, scuba diving) and recreation on the lake side. Lake Grevelingen itself is a nature resort which is used for recreational purposes such as camping. The historical information of this case study is extracted from the following publications: (Blom et al., 2012, Huibregtse, 2013, Van Baars and Van Kempen, 2009, Goemans and Visser, 1987, Nienhuis, 2008, Montauban, 1990, Orr et al., 2007) as well as from the following websites:

- http://www.geschiedenisvandirksland.com/geschiedenis/deel4.html
- http://www.digibron.nl/search/detail/012df7b8f86388c46e2e63fe/het-grevelingenmeer-sterft-langzaam-af

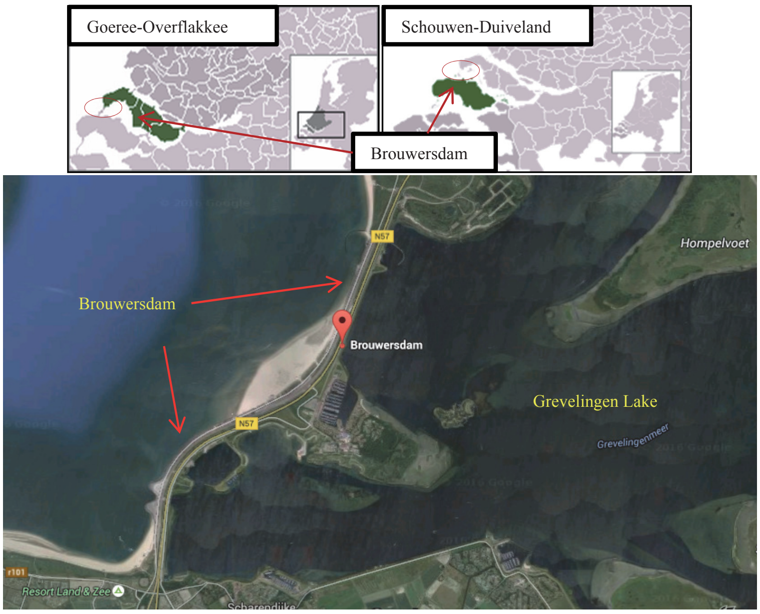

Figure 3, the Brouwersdam (modified from Google Maps)

By 1930, it was already known that the dikes in the river basins in province of Zeeland in the south of the Netherlands were too low and too weak to withstand high water levels and waves. Due to the consequences of World War II, there was lack of fund and so the dikes in this region had never been raised again. At that time the organisation and prioritisation of flood defence measures was very poor too. Therefore, when a north-western storm combined with spring tide led to a very large storm surge on the North Sea in 1953; Around 140 dike failures occurred throughout the Netherlands resulting in loss of life of about 1800 people and property damage displacing about 100,000 people. The reaction of the Dutch Government to the disaster was to launch the national 'Delta Works' to prevent such a disaster from happening again. As part of the Delta Works, it was decided to close off the estuary of Grevelingen from the North Sea.

With the aim of shortening the coastline of the Netherlands and to minimise the construction material needed, the location and trajectory of the dam was chosen in such a way that it would cross the Grevelingen over the former ebb-tidal delta. It was a difficult project because the water was deep (up to 30 m) and the tidal flows were strong in this part of the estuary. After the start of construction work in 1962, the Grevelingendam was completed in 1965 followed by the Brouwersdam in 1971 which totally cut off the Grevelingen estuary from the North Sea. It was decided to cover the dam with asphalt although the sea side was covered by grass. After construction of the road over the Brouwersdam, the structure became open to the public in 1973.

The Brouwersdam was constructed using 12 caissons with dimensions 68 m long by 18 m wide, enabling the estuary flows to be controlled. Following the construction, 3,000 hectares of dry land were created and the brackish lake of Grevelingen started to form. The water of the Lake Grevelingen was initially very clear such that in some places one could see to a depth of 9 m. In the 1970s the shallow water areas (shoals) at the lakeside acquired a new function as a beach, and the seaside became popular for water sports such as wind and kite surfing. The initial plan for the area was to transform the lake to a freshwater reservoir to support agriculture. However, the disappearance of the tide and the slow desalination of the lake had negative effects on the flora and fauna, meaning that many species became extinct and others appeared. Therefore, during the 1970s it was decided to halt the desalination and return the lake's salinity to the level before the closure. This resulted in the construction of the Brouwers sluice completed in 1978. Simultaneously, various tourist facilities were developed on the newly created beaches on both the North Sea side and the lake side.

The construction of the Brouwersdam and its use for various purposes has had significant impacts on the area. For example, the substantial changes in the tidal system of the Grevelingen estuary have resulted in the creation of a beach on the North Sea side of the dike but also continuous beach relocation and elongation towards the North-east. The decreasing width of this beach causes it to lose its recreation function, especially if erosion persists. This is an unwanted development for the users and stakeholders of the area, and the on-going beach relocation has led to the closure of one of the pavilions in the area. Later, the pavilion was relocated to a different beach a few kilometres away, although this too was unsuccessful. The relocation of the beach has also taken it away from the road that leads from the holiday park on Lake Grevelingen to the beach.

Another adverse outcome concerns the water quality of the lake. This has gradually deteriorated because of the standing water. Lake Grevelingen is now faced with oxygen poverty, stratification and algal blooms during the summer months. There are increasingly large dead areas in the lake with no aquatic animal life and an obviously negative impact on both the sporting and commercial fisheries in the area. Another external factor is the growth in availability of cheaper flights that has created a competition for cheaper alternative holiday destinations in other parts of the world. All these factors together have meant that nature and tourism have experienced a decline in quality and quantity.

The construction of Brouwersdam, as part of the Delta Works, was initially intended to protect people against flooding from the sea. At that time there was no consideration of other factors which may evolve over time. Currently, there are plans to develop a large (lockable) opening in the Brouwersdam to enable water to flow between the North Sea and the lake in order to combat oxygen depletion. It is expected that improving water quality will also attract tourists again. Moreover, an impact assessment study of the area has predicted that the plans for opening the Brouwersdam will not negatively impact the employment and economy of the area.

2.2.3 Vlissingen: a planned multifunctional case

Vlissingen is a coastal city in the south-west of the Netherlands on the former island of Walcheren. It has a strategic position at the mouth of the River Scheldt (the most important waterway to the port of Antwerp in Belgium) on the North Sea. The city waterfront performs the role of a multifunctional flood defence, where two boulevards and a series of buildings have been constructed on top of a sea wall for a length of about 2 kilometres. The historical information of this case study is from the following sources: (Zeeland, 2002, Breukelman, 2012, Heijboer et al., 1999, Meijers et al., 2012, Gemeente-Vlissingen, 2013, Hanson et al., 2015, Goodlet, 2013) and Vergouwe (2014). Information from the following websites is also used:

- http://www.gemeentearchiefvlissingen.nl/geschiedenislokaal/vlissingen-in-vogelvlucht/vlissingen-na-1940.html
- http://vlissingen.com/nl/historie.php
- http://www.omroepzeeland.nl/nieuws/2016-01-15/961800/miljoenenverlies-fietsvoetveer-stoppen-optie

Figure 4, the multifunctional flood defence of Vlissingen (modified from Google Maps)

Despite having experienced many floods, Vlissingen did not have an adequate flood defence system at the beginning of the 20th century. When half of the city became inundated (up to 4 meters above mean sea level) in 1906, the city council finally reacted. The city's old dike, protecting the city centre since the 12th century, was reinforced and a water retaining wall was constructed along the beach.

From 1907, the beach and promenade were developed by the municipal authority. Several walking paths, a bandstand, many kiosks, and the Boulevard Ervesten were built on top of the sea wall. A staircase (with an iconic lion statue) was constructed in the wall to allow access to the beach. By 1920, the sea wall had become part of a multifunctional area which was famous for its excellent beach facilities and good infrastructure. Gradually, many villas for wealthy people were built along the boulevard and a promenade pier was added to the beach around 1930. Vlissingen beach was very successful and popular before World War II.

The prosperity of Vlissingen did not last long. Due to its strategic location in the Scheldt estuary and well-developed infrastructure, the Germans occupied the city and wrecked the promenade pier (constructed in 1936) in 1942. In order to free the route to the port of Antwerp and to force the Germans to expel the area, the Allies bombarded the dikes and sea walls and the German headquarters (including many beach facilities).This resulted in liberation of the area, but also large-scale evacuation of people and livestock, and in 1944 almost the whole of Walcheren Island was flooded. It took almost a year for area to become dry again.

After the war, Vlissingen was dilapidated as such an extent that there was not a single house without damage and only a few remaining inhabitants. The breaches in the flood defence of the city were plugged in 1945 requiring over 250,000 trees as well as 2,000 tonnes of stone shipped from Belgium. Despite the efforts, the dikes were not strong enough to survive the disastrous flooding of 1953. The number of victims in Vlissingen was limited to three people since the city had not repopulated after the war. Additionally, most of the dikes of Walcheren were designed as windward dikes, while in 1953 mainly leeward dikes failed causing less casualties.

The delta works and post-war reconstruction brought prosperity to Vlissingen again. In the expansion planning of 1953, as suggested by President Roosevelt in 1950, the city adopted its 1907 classification as the backbone. The harbour of the city was expanded between 1961 and 1964, and many businesses and companies settled around the port. Followed by the reconstructions, tourism increased sharply. Therefore, the multifunctional area around the Evertsen Boulevard was renovated in 1990s and exists in this form today. This boulevard starts at the site of a historic villa (the Wooldhuis) and continues to the highest building in

Vlissingen (the Sardijntoren tower). From the Sardijntoren tower another boulevard (Boulevard Bankert) extends along the beach as a promenade with a rough slope towards the sea. Currently, the Sardijntoren tower consists an underground parking area, a ground level restaurant with a higher (than normal) ceiling, and a number of residential apartments on top. The Sardijntoren Tower has been designed to accommodate future sea level rise in such a way that the ground floor can be filled in and act as a part of the flood defence in the future.

The prosperity of Vlissingen, however, did not last long again. The ferries in Vlissingen were the only means of transport between Zeeuws-Vlaanderen (to the south of the Delta area) and the central part of Zeeland and the Dutch mainland, apart from the considerable detour through Belgium via Antwerp. It was decided in 1995 that maintaining the car ferries would be more expensive in the long term than a tunnel. Construction of the Westerschelde tunnel started in 1997 and was finished in 2003. A less frequent ferry for transporting pedestrians and cyclists came into service between Vlissingen and Breskens. The relative accessibility of places on both sides of the river has dramatically impacted tourism and employment in Vlissingen. Impact assessment studies have shown that the tunnel has also changed the demographic pattern of the area such that households with children have relocated from relatively less accessible to relatively more accessible areas (Meijers et al., 2012). Moreover, the demand for the ferry currently is less than 25% of the predicted value and is losing money. The city authority is working to improve the tourist attraction of Vlissingen, especially to increase profitability of the beach facilities.

2.2.4 Afsluitdijk: a planned multifunctional case

The Afsluitdijk is a closure and a major causeway in the north of the Netherlands (Figure 5). It connects the small city of Den Oever in the province of North Holland to the village of Zurich in the province of Friesland. The Afsluitdijk has disconnected the former Zuiderzee, the salt water inlet of the North Sea, which has now been transformed into the fresh water lake of IJsselmeer. The closure can be decomposed into a dike, a cycling path, a four lane highway, 2 navigation locks, and 25 drainage sluices. The two navigation locks in the both sides of the closure are used for the passage of shipping traffic and the drainage of water. The North Sea side of the closure forms part of the nature reserve Natura 2000. The historical information for this case study is from the following sources (Veraart, 2014, Steenbergen et al., 2013, Kabat et al., 2012, Snelder et al., 2007, Janssen et al., 2014).

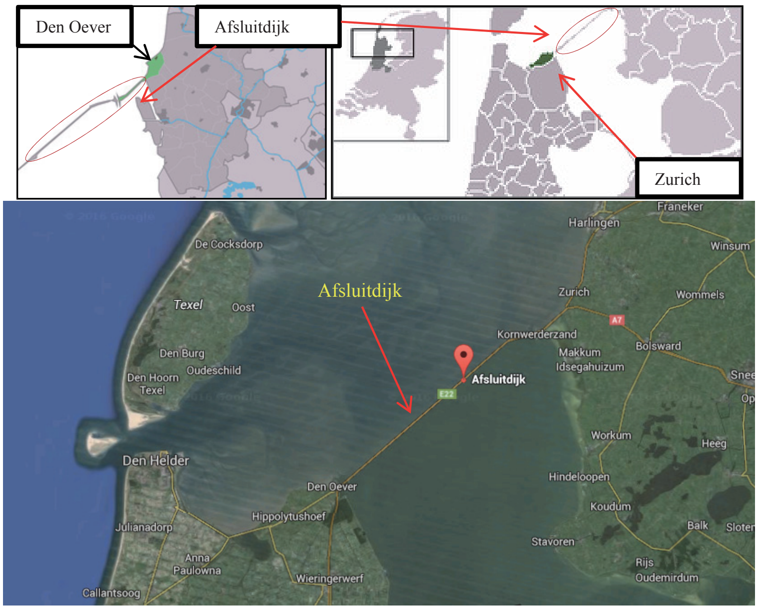

Figure 5, the Afsluitdijk (modified from Google Maps)

Before the construction of Afsluitdijk, the Zuider Zee was a large inland see in the northern part of the Netherlands from about the beginning of the late Middle-Ages until 1932. Initially, the Zuider Zee arose as a result of a series of floods causing land disappearance. The area was actively used for fishing reaching a peak in the early 1900. The surrounding areas of the Zuiderzee experienced frequent flooding, promoting plans as early as 1667 to prevent flooding around the Zuiderzee by damming the channels between the islands in the Wadden Sea.

During the nineteenth century, as technology quickly progressed, these plans were given a more concrete form. A thorough study of technical feasibility was made in 1889 leading to a concrete plan for the closure of the Zuiderzee and reclamation of land (Flevoland). At that time the plan was vigorously opposed by fishermen who were concerned by the threat to their source of income. Political forces had, until the disastrous flood of 1916, resisted the very ambitious, expensive and complex plans to dry out the Zuiderzee to reclaim the land. However, the food crisis during World War I promoted the need for land reclamation for agricultural activities. It was the loss of life of 50 people during the flood of 1916 that had the biggest influence on realising these plans.

A plan for the project was ultimately approved in 1916, after the flood rekindled interest in a proposal from 1889 which, at the time, lacked both sound engineering planning and government support. The closure of the Zuiderzee first started in 1920 by construction of the 2.5 km long Amsteldiepdijk from North Holland to Wieringen Island. This was followed by construction of the 32 km Afsluitdijk from four points which started in 1927. The tidal inlet was gradually closed and the last opening was sealed in 1932, where there is now a commemorative statue of a stoneworker.

It took nearly four times longer than the construction time for the land to become dry and usable. Unsurprisingly for a project spanning such a long period of time, the plan needed to be continuously updated and revised to reflect the changing needs of Dutch society. For example, instead of converting the newly acquired land for agricultural uses, some areas were designated for urban expansion.

The closure had major consequences for both fisheries and nature. The dam closed off the Zuiderzee and created Lake IJssel, forming what is now the largest fresh water body in the Netherlands. Desalination of the lake water denied work to thousands of fishermen who previously earned their income in the Zuiderzee. Other impacted groups were poultry farmers, fishmongers, sail makers and shipbuilders. Around 1939, ideas for biological conservation were discussed, but it was in 1970 that the Wadden Sea became a nature reserve of global importance and a World Heritage Site for its unique natural value. It is designated as a Natura 2000 site in order to maintain and improve biodiversity in the area.

After the official opening of the Afsluitdijk to road traffic in 1933, it has been modified at certain locations. The dike experienced an unsuccessful attack by the Germans during World War II and resisted the flooding event of 1953. The initial plan included a railway connection along the closure which was abandoned because a profitable operation proved impossible at the time. Instead, part of the original railway line was used to convert the existing highway from two lanes to four lanes in the 1970s.

The Afsluitdijk was primarily constructed to provide safety against flooding and to allow a cheaper construction of the polders in the IJssel Lake. Besides its main function, the Afsluitdijk has several other functions including water management (providing fresh water for drinking and agriculture); transport (via the highway and navigation locks), housing, recreation and tourism. Due to the ecological value of the lake, the plan for further reclamation in the lake was abandoned in 2003. It has, however, been realised since 1989 that the presence of two sluices is not enough to compensate for rising sea levels, land subsidence, and increased supply of river water to the IJssel Lake. It was decided to construct a third sluice in 2003, and in 2007 that the government announced the start of a 15 year plan for reinforcement of the Afsluitdijk. There are on-going studies for how to improve the dike, taking into account that there is no space available for dike reinforcement. The sea side of the dike has been nominated for Natura2000 and cannot be used for widening the dike. At this moment the government decision (as stated in the Dutch national water plan 2015-2021) is to combat the rising sea-level by constructing a pumping station.

2.3 Case study findings

This section presents the main findings from the case studies. First, the observed drivers of change are discussed and characterised. Afterwards, the factors affecting response of the system are described. The gained insights are then used to reflect on the practise of design and management of multifunctional flood defences under uncertainty and to determine the three specific objectives of the dissertations in the next chapter.

2.3.1 Characterising drivers of change

This section discusses the characteristics associated with the observed drivers of change. It can be clearly seen in the case studies that the land use changes, in majority of the situations, have happened as a result of human influence. These human induced changes have been due to either the decisions of local stakeholders or the consequences of the decisions made by the people outside the geographical boundaries of the system. Herein, the local (direct) stakeholders are assumed to be part of the system. Hence, their decisions are taken as internal driver of changes to the system. Every other driver that has influenced the local decision makers is thus considered as an external driver to the system. For instance, the decision on construction of the Afsluitdijk was partly made by the stakeholders involved in decision making on flood protection of the areas around the IJssel Lake (internal to the system). In another example, the decision on bombardment of the dikes in Walcheren was made by Allies who were not among the local stakeholders (external to the system).

The external drivers of change are investigated in this section from different points of view. The gained insights are then used to reflect on driver's predictability in the end of the section.

Driver's type:

Based on the Millennium Ecosystem Assessment (MA) presented in Leemans et al. (2003), the external drivers of change can be grouped by:

- demographic
- economic
- socio-political
- scientific and technological
- cultural and religious
- natural (physical, biological, and chemical)

Using the Millennium Ecosystem Assessment, almost all of the listed external drivers of change were clearly observed in the case studies including the demographic, economic, socio-political, scientific and technological, and the natural and physical drivers (summarised in Table 1). The available information about the case studies does not explicitly indicate whether any cultural and religious driver was involved in the land use change decisions.

Since the four case studies are located on the coastline of the Netherlands along the North see, all of them have become impacted by flooding of 1953. Afsluitdijk and Vlaardingen have also become impacted by the flooding event of 1916. Although the two events resulted in significant losses, the flooding events were not the direct cause of land use change in case studies. In other words, the usage of the land was not changed immediately after the flooding. Rather, they created the momentum to change the land use in order to improve flood protection for the future. Furthermore, although the Allies bombardment (in Walcheren) resulted in flooding of 1944 (during WWII), the direct cause of land use change (destructions of the dikes in Walcheren) was the human decision, but not the nature itself. Hence, it can be argued that flooding, as a physical and natural driver, has not been a direct external driver of change in the land use at the time of occurrence.

The situation is slightly different for the Brouwersdam. Algal bloom represents a natural driver that has directly changed the water quality of the Grevelingen Lake. In that sense, the system function has been directly impacted by a natural driver. While the identity of the whole system as a combination of a flood defence and lake has not changed, the function of the lake has changed from becoming a fresh water lake to become brackish lake. On the other hand, the water quality problem has also impacted the touristic function of the lake. In this case study, the algal bloom is already a problem caused as a side effect of the prior decisions of the local stakeholder, which in turn forces the same local stakeholders, to make new decisions for improving the case. Thus, it is not just the algal bloom alone, but the interactions between natural and social drivers that have impacted the land use.

The natural driving forces of the case studies did not have sufficient power to change the use of land directly. It can therefore be emphasized that the human activities, both internal and external to the system, have been the major driving forces shaping the evolution of multifunctional flood defences in the past.

Driver's spatial scale:

Following the terminology of Petschel-Held and Bohensky (2005), the spatial scales of the drivers can be divided into the local, national, and global. The spatial scale in this section implies for the extent of the immediate influence of a specific driver. For example, a flood event can be a local or national scale driver depending on how large the extent of the event is. In another instance, A global driver is, however, a driver that affects more than one country (Hazell and Wood, 2008). For instance, the World War II (WWII) had a global impact at the time of occurrence.

What can be seen in the cases is that the scale of influence of the drivers has gradually expanded from local to global in the course of the 19th century. For example, the decisions on improving the flood defence of Vlaardingen after the flooding of 1916 and the flood defence of Vlissingen after the flooding of 1906 were made based the national interests. Currently, it is not easy to decide for improving the Afsluitdijk in the future only based on the national interests. This is because, nowadays, the Wadden See side of the Afsluitdijk belongs to Natura2000. Thus, the improvement of the flood defence has to address the requirements of Natura2000, which is a global initiative. In this case the biological globalisation (Keohane and Nye Jr, 2000) is a driver that will determine to what extent a local driver can influence the land use change decisions.

Another example is related to globalisation of the economy (Schulze and Ursprung, 1999), the regional, national and global economy have become closely interwoven. This has happened because greater benefits can be gained from the specialisation of production processes on a global scale (Kabat et al., 2012). As a result, a driver of change happening in one part of the world, which was not previously expected to affect an area, can also lead to the land use changes. An example of this situation is the rise of cheap international flights which has negatively impacted the tourism in the recreational areas around the Brouwersdam.

Driver's temporal scale:

According to Petschel-Held and Bohensky (2005), the temporal scale of a driver can refer to the 'speed at which the driver operates' or 'the speed at which the driver changes'.

It can be seen in the case studies that the time period at which a driver operates can be as short as a few minutes (e.g. bombardment) to a few hours (e.g. duration of extreme water levels) to a few years (e.g. WWII) or even to a few centuries (e.g. climatic changes).

Regarding the speed at which the driver changes, it was also observed in the case studies that are some drivers of change that have occurred in the past and have already impacted the land use. On the other hand, there are some other drivers that are occurring now and are expected to impact the land use in the future. In this research, the former drivers are addressed as the *drivers of the past* and the later drivers are addressed as the *drivers of the future*. Table 1 summarizes these two groups of drivers of change. While it might be possible to collect information to study the *drivers of the past;* it can be seen that, at least, due to the changing context of the drivers, the gained knowledge and information about the past may not necessarily help in understanding and anticipating the *drivers of the future.*

Table 1, the ‘drivers of the past’ are presented in the white cells and ‘drivers of the future’ are presented in the grey cells. The column ‘time’ demonstrates the decade in which the specified changes occurred.

Case study	Time	Driver description (type/scale)	Resulted changes
Vlaardingen	1910s	• City expansion (economic/local) • Growth of vulnerable population (demographic/local) • Flooding of 1916 (natural/national)	Construction of a higher embankment resulting a multifunctional flood defence
	1950s	• Post war economic growth (economic/local) • Flooding of 1953 (natural/national)	Increasing the height of the embankment for flood safety
	Present	• Groundwater flooding • Sewerage	Requires some changes to the urban drainage of the city
Brouwersdam	1970s	• Flooding of 1953 (natural/local) • Creation of the beach (natural/local) • Creation of the lake (natural/local) • Tourism demand (economic/national)	Closing off the estuary resulting in a multifunctional area
	Till present	• Beach transformation (natural/local) • Algal bloom in the lake (natural/local) • Access to cheaper flights/ resorts (economic/global)	Abandonment/relocation of the recreation facilities created in the area
	Present	• The water quality problem (natural/local)	Requires an opening of the estuary to enable tidal movement
Vlissingen	1900s	• Demand for tourism (economic/global)	Creation of beach facilities around the sea wall
	1940s	• German invasion during WWII (socio/political- global) • Allied bombardment strategies (socio/political- global) • Intended flooding of 1944 (socio-political-/global)	Destroying the beach facilities and causing large scale damages
	1950s	• Post war reconstructions (economic/demographic/local) • Flooding of 1953 (natural/local)	Reconstructions of the beach facilities at the sea wall
	1990s	• Transportation demand (economic/national)	Abandonment of some beach facilities due to lack of demand
	Present	• Lack of demand for tourism (economic/global)	The need to improve the touristic attraction of the area
Afsluitdijk	1910s	• Food crisis caused by WW I (economic/global) • Flooding of 1916 (natural/local)	Acceptance of the ambitious project proposal
	1930s	• Technological advancement (science and technology/national)	Construction of the dam +road+ land drainage)
	1970s	• Transportation demand (economic/national)	Construction of the second line of the highway
	Present	• Natura2000 (natural/global) • Sea level rise (natural/global)	Limiting the possibilities for widening the dike

Drivers' interaction and pluralism:

It can be seen that the human decisions are the direct cause of land use change in majority of the cases. These human decisions have actually been formed based on the impact of other driving forces that had happened before. As also argued by other scholars such as Clark (1985), Winemiller (1996), Pielke (1999), Lee (2011), McEwan et al. (2011), Elmhagen et al. (2015) the drivers of change interact over a tremendous range of temporal and spatial scales. In fact, it is a mixture of multiple interacting factors that result in significant changes in land use.

For instance, the decision to close the Grevelingen estuary and construction of the Brouwersdam resulted in significant changes in land use due to creation of a new beach and the Grevelingen Lake. However, the developments initially promoted tourism in the area. The human induced changes in the tidal system of the estuary resulted in beach relocation and water quality problems, reducing the touristic value of the area. Clearly, the current situation in the location of Brouwersdam and Grevelingen Lake is the result of the interactions between the drivers of the past and the drivers of the future.

Driver's predictability:

From the temporal point of view, the socio-political drivers (e.g. WWI, WWII, food crisis after WWI) and the non-human induced natural drivers (e.g. Floods of 1016 & 1953) represent the emergent phenomena which have happened without a prior notice. Predictions of such changes were beyond the scope of the local decision makers.

The economic drivers (e.g. tourism demand changes), demographic drivers (e.g. change in the Vlissingen population after war), the human induced natural drivers (e.g. the morphological changes in Brouwersdam), represent a more gradual rate of change. However, the instigation of change may have not been predictable many years in advance. The gradual rate of change enables trend prediction with a limited degree of precision in some cases.

For example, perhaps, it has not been possible for people to realise the emergence of climatic changes many decades ago, but it is now possible to anticipate the future direction with a limited certainty. Most notably, every case study has experienced some surprising events (e.g. WWI & WWII) which were not predictable at all, but have significantly influenced the land use. The same can be claimed about the spatial scale of the drivers. Nobody could predict the scale of impact of WWII in the beginning of the war. Today, it is still not possible to predict the local scale impacts of some known drivers of change such as climate change.

Overall, it can be seen that the drivers of change emerged, evolved, interacted, and aggregated each other's impacts vey dynamically and in very complex and non-linear ways. Although, it might be possible to predict the duration of influence of some drivers of change, such as the duration of extreme water levels; it is not yet possible to predict the emergence of some future drivers. Due to complexity of human behaviour, it is especially hard to predict the human induced changes of future, like the timing and extent of terrorist attacks or the wars. Therefore, it can be said that with the current knowledge limitations, it is hardly possible to model the complexity of drivers' emergence and interactions.

2.3.2 The response to change

The preceding section discussed the characteristics associated with the drivers of change. In addition to the drivers' characteristics, it can also be seen that there are some other (internal) factors that are also the determinants in how the use of land has changed. This section discusses some of these characteristics as identified in the case studies.

The affectability of land use:

Although the whole Netherlands became impacted by the consequences of WWI and WWII, the multifunctional beach of Vlissingen seems to be the most impacted by WWII. However, the Afsluitdijk experienced an unsuccessful attack during WWII. It was the food crisis of WWI which significantly impacted the decision to construct the Afsluitdijk. The WWI did not explicitly impact the other cases. Clearly, the same driver has not have the same impact on two different cases.

In another example, the processes involved in sweetening of the Lake Grevelingen and Lake IJssel were the same. While IJssel Lake is valued as a fresh water reservoir, the sweetening process became very unpleasant in the Grevelingen Lake. Aligned with the arguments presented in Pahl-Wostl (2007a), Grimm et al. (2008), and Alberti (2005), it can be said that the type and extent of the impact of a driver on a specific area, depends not only on the type of the driver, but also the context and history of a specific case study.

Complexity of internal interactions and dependencies:

Up to the time the railway of Vlaardingen was only intended for transportation, making decisions on it was the task of the stakeholders involved in transportation. After combing the function of flood protection with transportation, making decisions on the railway needs to address the flood protection requirements as well. Thus if a driver of change (e.g. heavy precipitation) would have occurred before 1916, the response of the decision makers on whether the railway needed to bear any change could have been totally different than during the time after reinforcement of the railway as a flood defence. In this case, combining the functions has created dependencies between their performances that have impacted the response to a driver of change.

Repeatedly, it can be seen in the case studies that the purpose of the land use has been changed from the 'planned for' to 'become for' domain. For example, in the case of the Afsluitdijk, it took many years for the whole project to be completed. In the meanwhile, the change in the societal preferences resulted in significant changes in the layout of the project. The planned railway was not realised and was replaced by a highway construction; and the drained land was never used for agriculture, but for urbanisation. In fact, the use of land has undergone various changes it was not conceived for. In this situation, the complex interactions between the system components (land use and local decision makers) and its external environment has been an important factor in shaping the response of the system to a driver.

The power of flexibility:

As it can be seen in the case of the Brouwersdam, the current system design does not allow for the ease of solving the problem of algal bloom. This is an example of a multifunctional flood defence with lack of sufficient design flexibility to adjust the system. In contrast, the case of the Afsluitdijk demonstrates a degree of flexibility in the design of the flood defence and the secondary function of the system which enabled changing the land use purposes later on.

These observations along with the observed characteristics of change in the case studies, have two strong indications: the absence of flexibility can result in a situation, which could have been adjusted and modified easier otherwise; and that the presence of flexibility can enable making a better use of the emerging opportunities by enabling the ease of adjustment to the new conditions. In other words, the capability of a system to handle changing circumstances will depend on whether the flexibility exists to address the new requirements (Folke et al., 2005).

Furthermore, it is seen that the secondary function of a multifunctional flood defence can potentially contribute to handling the uncertainty in the design and management of the flood defence. For example, the embedded design flexibility in the high rise building located on top of the sea wall in Vlissingen enables the ease of flood defence reinforcement in the future. The design flexibility embedded in the secondary function of a flood defence can also reduce the need for a higher dike at the present time.

As it can be inferred from the case studies, the flexibility provided to the decision makers at the time of changing conditions had not been deliberately embedded in the system, except in the case of high rise buildings in Vlissingen. Gradually, it has become known that the presence of flexibility is a system attribute that can assist in handling unexpected future changes. Currently, the need for increasing the flexibility of flood protection strategies is also part of the central intention of the Dutch Delta Program. The goal is to devise flood protection strategies that can maximise flexibility while reducing flood vulnerability and maintaining cost-effectiveness (Van Alphen, 2015).

2.4 Reflecting on case study findings

It can be seen in the case studies that the relationships between the occurrences and consequences of drivers and evolution of the land use are very complex. It is hard to imagine that decision makers could predict a century of drastic changes earlier in 1900s. Indeed, understanding of the drivers of change as well as the change processes has always been- and is still partial. Moreover, the available information about the drivers of the past is not sufficient to explain the complexity of the drivers' interactions in the future. Observing that the context of the some known *drivers of the future* is even different than the *drivers of the past*, it is not possible to assume that the future can be predicted based on extrapolation of the past.

As opposed to this observation, the common tendency in many research works presented in the literature, especially in the area of engineering, is still to assume that the 'present is the key of the future' (Sier and Monteith, 2016, Johansson, 2015). This assumption implies that there is enough knowledge available at present time to be able to extrapolate the information forward to predict the future. Accordingly, various methods have been developed with the aim of predicting future changes with the use of the historic data (Carter et al., 2007, Muis et al., 2015). Two very common computational practices in the engineering community are based on statistical analysis of the past data and model based simulation of the future (Rosner et al., 2014, Ludwig et al., 2014). In both methods, the objective is to develop theories and derive relationships between observations and the theories (Furlani and Ninfo, 2015). The case study observations demonstrate that none of these methods are capable of predicting the future as intended. In short, the ability to predict the future is still very limited for the following reasons:

1) The information about past events is rare. However, historical documents help to understand some characteristics of variability and change. Quantitative data is often unknown (Di Baldassarre et al., 2015), lacks reliability (Pielke, 1999, Papathoma-Köhle et al., 2015), or have been subjected to human cognition biases over time (Changnon, 2003, Merz et al., 2015).

2) The future is not a simple extrapolation of the past. There are a seemingly infinite number of combinations of processes that play out across enormous ranges of space and time scale to form the future (Schindler and Hilborn, 2015). It can be well expected that a multifunctional flood defence can be evolve in the future in unimaginably different ways. Hence, extrapolation of past events can be full of wrong assumptions, unknowns and surprises (Di Baldassarre et al., 2015).

3) Probabilistic models of the future address only a limited set of parameters. These probabilistic approaches suffer from a number of limitations related to the subjectivity of the probability distributions and difficulties in handling multiple sources of uncertainty (Furlani and Ninfo, 2015).

In view if of the significant influence of the drivers of change on the existence and performance of multifunctional flood defences, developing approaches to handle uncertainties about future circumstances can be considered as a key area of improvement in the design and management of multifunctional flood defences. In doing so, a key question is: how to develop alternative design and management strategies that would be better at coping with the complex internal and external changes that that can frequently move a multifunctional flood defence out of the domain it was conceived for?

In the pursuit of answering this question, this research will explore and contribute to develop an approach to assist the decision makers in coping with uncertainty in the design and management of multifunctional flood defences. In doing so, the next section discusses various approaches for handling uncertainty and change that have already been developed and presented in the literature.

3 Handling uncertainty and change: literature review

"We must now increase efficiency, reduce cost and improve quality.
Action will be needed on several fronts.
We must reduce unnecessary and multiple levels in decision making and provide greater flexibility and scope for initiative."

Indira Gandhi in 1987

3.1 Background

Traditionally, infrastructure systems are designed with the expectation of being cost-effective. This implies maintaining the desired system performance at the lowest costs for a predetermined time period. Achieving such effectiveness requires successful control of the system and its environment (physical, technical, political and institutional). To do so, it is assumed that the system environment can be perceived as an orderly, rational, physical world that can be engineered, controlled, and managed (Merchant, 2015). The success of the control process will depend on the ability of the controller to predict the effect of potential control actions as well as the ability to develop sufficient control actions to cope with the variability of the system. Enabling this capability requires sufficient information availability and the presence of an accurate model of the controlled system and its environment (De Leeuw, 1976, De Ridder, 1994, Demirel et al., 2013, Van Riel et al., 2015).

Today, it is well known that the tradition of constructing technical systems such that they can be controlled, cannot address the needs of a deeply uncertain future (Lempert et al., 2003, Hallegatte et al., 2012). It has already been addressed in the literature that ignoring uncertainty can result in the lack of possibility to take advantage of future opportunities and/or lack of ability to take corrective actions in order to prevent unfavourable situations (Walker et al., 2013). The case studies of Chapter 2 showed that the current situation is not necessarily as expected at the time of flood defence design. For instance, the initially expected profitability from the developments on top of the sea wall in Vlissingen did not materialise. This is because only one optimistic scenario (with static assumptions) was taken into account in the initial design phase, and therefore, the possibility to change the purpose of the developed area was not addressed.

The case study observations strongly support the statement of Milly et al. (2007) that 'stationarity is dead'. In other words, ignoring uncertainty by means of making 'stationary' or 'static' assumptions about the emergence, evolution, interaction and impacts of the drivers of change is not a rational choice anymore. Instead, it is acknowledged in the literature that the future developments are expected to be path-dependent and context-sensitive, and the system itself will remain in constant change (Pahl-Wostl, 2007a, Bagheri and Hjorth, 2007, Halbe et al., 2013). Consequently, the desire for controllability has gradually been replaced by the need to increase the system's capability to adequately deal with future changes (Ross et al., 2008, Kincaid, 2000, Gifford, 1996, Masood et al., 2016).

This chapter presents a brief review of the literature on the approaches for handling uncertainty. It is acknowledged that there are many different types, sources, and levels of uncertainty (as defined in: Walker et al., 2003) that can affect the design and management of multifunctional flood defences. Here in this research, uncertainty is referred to as the factors that are known only imprecisely, or are not known at all; the so called deep uncertainty as defined by Lempert et al. (2003). The insights gained from the literature together with the findings of the case studies (presented in Chapter 2) are then used to specify the objectives of this dissertation at the end of this chapter.

3.2 Review of literature

A review of the literature demonstrates that 'adaptation' has emerged as an important area of research and assessment among scientists dealing with uncertainty. In particular in the climate change literature, it has long been reported that due to the uncertainty about various interactions within social, biological, and physical dimensions of global change, climatic changes can have surprising consequences in the future (Clark, 1986, Schneider and Root, 1996). More recently, adaptation to climate change has gained increasing interest as a way of handling uncertainty about the future (Burton, 1996, Peterson et al., 1997, Smith et al., 2000, Grothmann and Patt, 2005). In this regard, the Intergovernmental Panel on Climate Change (IPCC, 2001) defines adaptation to climate change as the ‘adjustment in ecological, social or economic systems in response to observed or expected changes in climatic stimuli and their effects and impacts in order to alleviate adverse impacts of change or take advantage of new opportunities.

The earlier papers on adaptation practice (in the 1960s) are still based on the dual control theory with the goal of understanding and controlling system behaviour (Feldbaum, 1961, Burton, 1996). Later on in the 1970s, the term ‘adaptive management’ appeared in the literature. Walters and Hilborn (1978) were among the first to use this term for addressing adaptive approaches in social contexts. They argue that the ability to predict the future key drivers influencing an ecosystem, as well as system behaviour and responses, is very limited. It is acknowledged that handling uncertain future changes requires the capacity to learn over time. Therefore, management interventions should be formulated as experiments. The information from follow-up monitoring is then used to improve subsequent actions in the light of that experience (Grumbine, 1994, Lee, 2001, Williams et al., 2007). In this way, adaptive management represents an evolutionary approach based on trial-and-error, which copes with the changing conditions in a reactive way (Rogers, 1998, Stankey et al., 2005).

Besides the term ‘adaptive management,’ ‘adaptation planning’ has also been addressed in the literature as a proactive response to anticipated changes in the future. Similarly, Sonka and Lamb (1987) suggest that instead of adapting to change once it has occurred, more useful insights could be gained from analysing and adapting to the evolving conditions. The application of the term adaptation planning to land use development dates back to Bolan (1967) who describes the benefits of adaptation planning in taking advantage of the opportunities created in the future.

Furthermore, the terms ‘adaptive policy making’ (Walker et al., 2001), and ‘planned adaptation’ (Füssel, 2007) have also been used in the literature referring to actions undertaken to handle anticipated climate change impact. Building upon previous studies, Haasnoot et al. (2013) have developed a method called ‘dynamic adaptive policy pathways’. This method further improves the ‘adaptive policy making’ with the use of ‘adaptation pathways’. The adaptation pathways provide an analytical approach to assist in selecting and prioritizing among the adaption policies, including many different types of actions that can be taken to adapt to climatic changes.

Following the advances in the field of adaptation to climate change, this research also focuses on anticipatory adaptation planning. The adaptation process, as applied in this research, includes a continuous stream of activities, actions, decisions and attitudes designed for learning from the past in order to develop better strategies for coping with the deeply uncertain changes in the future. In this regard, two approaches have been addressed in the literature to prepare for anticipatory uncertainty management: 1) to design the system under consideration in such a way that it can continue its desired performance under changing conditions, without the need for significant system modification. Increasing the system resilience and robustness are central to this approach; and 2) to increase the flexibility of the system to enable ease of modification and adjustment along with the changing circumstances (Thissen, 2012, Walker et al., 2013, Anvarifar et al., 2016).

3.2.1 Resilience

As reported in Davoudi et al. (2012) the term resilience was first used by physicists to describe the characteristics of a spring and to explain the stability of materials and their resistance to external shocks. Since the 1960s, resilience entered the field of ecology when Holling defined resilience as 'the ability of a system to absorb change and disturbances and still maintain the same relationships between … state variables' (Holling, 1973). Following Holling's work, a resilient system has been often characterized as a system that is able to absorb disruptions while maintaining its present identity and stability domain (Brugge, 2009, Walker et al., 2004, Gersonius, 2012). The role of resilience in adaptation planning is summarized by Walker et al. (2013) as 'whatever happens in the future, make sure that the system can recover quickly'.

The notion of resilience has gained increasing prominence within the adaptation literature. The frequent use of terms such as 'climate proofing', 'climate resilience', 'resilient city', demonstrates the popularity of the concept which emphasizes improving the ability of cities and urban infrastructure to quickly bounce back from climate-related shocks and stresses (Kabat et al., 2005, Vale and Campanella, 2005, Zevenbergen et al., 2008, Tyler et al., 2010, Leichenko, 2011, Friend and Moench, 2013, Bahadur and Tanner, 2014, Jabareen, 2013). In this regard, some recent work in flood risk management with focus on resilience includes efforts to: develop resilience indicators for evaluating resilience (De Bruijn, 2005, Schelfaut et al., 2011, Escarameia et al., 2015), investigate the usefulness of different climate change adaptation methods that are aimed at increasing resilience (Gersonius, 2012), and address various options for building resilience in cities such as Rotterdam (Dircke and Molenaar, 2015, Spaans and Waterhout, 2016) and Boston (Newman et al., 2013). Several recent studies also present some mechanisms to increase the resilience of urban systems (Wardekker et al., 2010, Thompson et al., 2009).

Increasing the resilience of socio-technical systems is, however, just one way of handling uncertainty. Other ways of handling the uncertain changes in the future focus on robustness and/or flexibility, which are further discussed in the following sub-sections.

3.2.2 Robustness

The term 'robustness' is addressed in the literature in two distinct ways: in one use, it is as an attribute of a decision, strategy or policy which is expected to have a better comparative performance over a large number of scenarios. Attached to this is the approach of 'Robust Decision Making (RDM)', where the term 'robust' characterizes the outcome of a decision or design (Hashimoto et al., 1982, Matalas and Fiering, 1977, Thissen and Walker, 2013). In this approach, an iterative, computer-based decision analytic framework is used to identify better performing strategies (e.g. the least sensitive) among the spectrum of possible changes (Ullman, 2001, Lempert et al., 2004, Lempert and Schlesinger, 2000). Perhaps, the most prominent use of RDM in the context of adaptation to climate change is linked to the RAND Corporation (Lempert et al., 2003). For example, Groves and Lempert (2007) use the RDM approach to identify strategies that are robust over a wide range of often poorly-characterized uncertainties. They claim that RDM can assist in determining the strategies that are the most important to the choices facing decision makers.

Hall et al. (2012) compare RDM to another method of robust decision making, the so called Info-Gap Method (Ben-Haim, 2006). They conclude that the use of robust decision making approaches can assist in identifying an improved set of decision making options, though deeper understanding of such methods requires further research. In this line, Daron (2015) examines the application of RDM in the context of developing countries. He concludes that the complexity of the decision making process (due to competing environmental, socio-economic and political factors) in these countries and the RDM need for combining quantitative data with qualitative understanding limits the application of the approach to the context of developing countries. Irrespective of the limitations of the approach, 'robust decision making' offers a systematic analytic approach and selection process to select amongst a set of proposed alternative strategies.

In addition to robust decision making, the term robustness is also used to describe the system property that allows a system it to satisfy a fixed set of requirements, and perform its intended function, for a defined period of time despite changes in the environment or within the system (Goulter et al., 1992, Saleh et al., 2003). As cited in Park et al. (2006) Taguchi a pioneer of developing robust design methodology in the 1980s, states that 'robustness is the state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in the manufacturing or user's environment) and aging at the lowest unit manufacturing cost.' Therefore, a robust system remains reliable without being significantly influenced by the extreme events under consideration and without the need to change under varying working conditions (Tsui, 1992, Fricke and Schulz, 2005). Similarly, Mens et al. (2011) use the term 'system robustness' to refer to a flood defence system's 'ability to remain functioning under disturbances.'

A brief review of the literature shows that both interpretations of robustness have been used extensively to handle uncertainty in the context of water resource management. For example, (Kasprzyk et al., 2013) combines a multi-objective evolutionary search approach with the principles of robust decisions making. They generate several alternatives for planning with the use of an evolutionary algorithm and evaluate them against an ensemble of scenarios. In another study, Kwakkel et al. (2015) develop a computer assisted optimisation method to search for robust dynamic adaptive policy pathways. In the context, of robustness in design, Mens et al. (2011) define three criteria of 'resistance threshold', 'proportionality', and 'manageability' to quantify what they call the 'system robustness'. In the same context, the two concepts of 'unbreachable dike' and 'delta dike' have been introduced in the Dutch engineering community to refer to a flood defence (a dike) which remains functioning without failure under a wide range of conditions (Van Loon-Steensma and Vellinga, 2014, De Bruijn et al., 2013, Voorendt, 2013).

Despite the widespread use of resilience and robustness as a system design principle in the literature, they both have limitations. Resilience and system robustness demonstrate anticipatory approaches in handling uncertainty. Both approaches focus on avoiding or alleviating the negative effects of uncertain future changes (e.g. sea level rise) (Dossou and Glehouenou-Dossou, 2007) in the initial design of the system. Hence, the possibility to actively make changes to the system in the future is not explicitly addressed. Ignoring the need for modifying the system when conditions change, may impede the system from responding to a change out of the anticipated situations and/or reduces the efficiency in responding to change. In particular, a robust system is sensitive to worst case scenarios (Hallegatte et al., 2012) and so the system may not be able to respond adequately if an event more extreme than previously anticipated occurs (McDonald and Styles, 2014). Indeed, there are always limitations to the extent of robustness of a system.

Apart from resilience and robustness, flexibility is another system attribute that has been introduced in the adaptation literature. Flexibility is addressed as a system capability that enables adjusting the system in accordance with future requirements.

3.2.3 Flexibility

Consideration of flexibility is generally proposed as an approach to assist the decision making with incomplete information (Schlesinger, 1965, Saaty, 1990, Polasky et al., 2011). In contrast to system robustness in which the system design (e.g. a flood defence) is expected to remain unchanged after it has been realised, flexibility is aimed at increasing the ability of the system to be changed (Fricke and Schulz, 2005). The proposed definitions of flexibility such as ‘uncommitted potentiality for change’ (defined by Bateson, 1972 , as presented in Demos, 1969), ‘the potential of a system for structural change’ (Pahl-Wostl, 2002), ‘ability to change in response to altered circumstances’ (Adger et al., 2005) and ‘plan to change over time, in case conditions change’ (Walker et al., 2013) all encompass flexibility as a capability to change or be changed rather than remain unaltered in time.

Many different types of flexibility have already been introduced in the literature. These include, but are not limited to: ‘institutional flexibility’ (Dominguez et al., 2009, Tompkins and Adger, 2005), ‘operational flexibility’ (Riebsame, 1988, Madani and Lund, 2010, Ulbig and Andersson, 2012), ‘strategic flexibility’ (Millar et al., 2007, Bettis and Hitt, 1995), ‘structural flexibility’ (Maurer, 2009), ‘flexible management’ (Larsen and Gujer, 2001, Halpin, 1997, Pahl-Wostl et al., 2007), and ‘flexible design’ (Middelkoop et al., 2001, Gersonius et al., 2013, Pahl-Wostl, 2009). In these uses, flexibility is understood intuitively without specifying its contextual meaning.

The use of flexibility for coping with extreme climatic events has long been addressed in the adaptation literature (Hanak et al., 2011, Riebsame, 1988, Gunderson, 1999). In particular, in the flood risk management literature, there is a growing interest in the concept of flexibility as a way of handling uncertainty. Flexibility is referred to as a system capability that promotes learning through time and increases the opportunities for reversibility (Kundzewicz, 1999, Hallegatte, 2009, Refsgaard et al., 2013).

A very common way of incorporating flexibility into flood protection decision making is via enabling staged development of flood defences. There is a trade-off between acting sooner or later which shows the value of embedded flexibility as well as the value of new information collected over time. It has been shown by several authors that enabling flexibility as such can explicitly account for uncertainty and incomplete knowledge (Gersonius et al., 2011, Lazarow, 2016).

Apart from the efforts in embedding and evaluating flexibility in flood risk management, there are a limited number of publications that have addressed other aspects related to the concept of flexibility. For example, Difrancesco and Tullos (2014a) define the five characteristics of ‘slack’, ‘redundancy’, ‘connectivity’, ‘adjustability’, and ‘cooperation’ to assess the flexibility of water systems. These characteristics are applied to measure whether the proposed management actions for flood risk management contribute to increasing flexibility of the system in achieving its predefined goals. In another study, Spiller et al. (2015) propose five mechanisms for increasing the flexibility of waste water systems, namely ‘robustness of design’, ‘platform design’, ‘phased design’, ‘modular design’ and ‘design for re-manufacturing’.

As it will also be discussed in Chapter 4, despite the clear indication of the potential to change as a prominent characteristic of a flexible system, there is no consensus across the literature about what constitutes flexibility, how to achieve it and whether it is worth making a system flexible.

3.2.4 Resilience, robustness, and flexibility: the shared aspects

The three concepts of systems robustness, resilience and flexibility are different in definition. Both resilience and robustness demonstrate a degree of system insensitivity to change. Where resilience encompasses persistence and recovery (McPhearson et al., 2015), robustness embraces resistance (Walker et al., 2013). A robust system is expected to remain unchanged before, during, and after a disturbance. A resilient system may not stay unchanged during the occurrence of a change, but it is expected to bounce back to its pre-disturbance state quickly. Both robustness and resilience are related to the system's stability in the face of possible external disturbances (Klein and Tol, 1997).

In contrast, flexibility refers to the capability to modify and adjust the system before and/or during a disturbing event. The embedded flexibility is intended to keep the system ready to satisfy a new performance requirement that may emerge in the future (Ajah, 2009, De Neufville and Scholtes, 2011). It is used not only to minimize unpleasant losses, but to acquire upside gains (De Neufville and Scholtes, 2011). In this way, flexibility refers to the ability to satisfy structurally changing requirements after the system has been realised (Saleh et al., 2003). Hence, from the point of view of system changeability, flexibility and robustness are each other's opposites.

In practice, resilience, system robustness and flexibility are not mutually exclusive. For example, Klijn et al. (2014) and Mens (2015) use the term robust flood defence to represent a system that can handle temporary external stress by combining the insensitivity to change (resistance) with easy recovery (resilience) in the aftermath of a stressing. This interpretation along with the terminology of Ruhl (2011) includes resilience as a subset of system robustness. Other scholars such as Ross and Rhodes (2015) and Nelson et al. (2007) categorise flexibility and system robustness as subsets of resilience. On the other hand, Levin and Lubchenco (2008) use resilience and system robustness interchangeably in the context of marine systems. While sometimes system robustness is seen as an essential characteristic of flexible systems (Spiller et al., 2015), flexible systems are also considered to be more likely to maintain an unchanged system performance (or a 'robust performance') (Loonen et al., 2013).

Perhaps one commonality between a flexible and a resilient system is that both terms refer to the situation in which the capacity for learning through time is taken into account in addressing uncertainties (Klein et al., 2003, Gersonius et al., 2013). Essentially, flexibility represents an active adaptation approach in which the external and internal changes to the system are constantly monitored. The system is then modified when the observed changes demonstrate the need for taking action. Resilience represents a more passive way of handling uncertainty since the system configuration is improved in the initial design phase in such a way to reduce the need for significant configuration changes in the future. Herein, the distinction between passive and active ways of handling uncertainty relates to when the system undergoes any configuration change to respond to uncertainty. The former indicates a one-time configuration change before uncertainty unfolds. The latter refers to any number of times of configuration change whenever uncertainty unfolds (McConnell, 2007, De Neufville, 2004a, Chalupnik et al., 2013).

Another point of confusion about resilience, system robustness and flexibility relates to the enabling mechanisms. Herein, a mechanism is considered as an action, decision or entity that enables the system to respond to changing conditions (Mikaelian et al., 2011). In the literature, mechanisms such as buffering, redundancy, staging, modularity and platform design are proposed as enablers of system flexibility (Spiller et al., 2015, Mikaelian, 2009, Halpin, 1997, Handmer et al., 1999). Mechanisms like scalability, modularity, resolvability, redundancy and buffering are considered in the literature as ways of increasing the system resilience (Ruhl, 2011, Wardekker et al., 2010). There are however scholars who consider redundancy (Schulz and Fricke, 1999) and buffering (Whitacre and Bender, 2010) as principal mechanisms enabling robustness.

The overlap in interpretations of resilience, system robustness, and flexibility has several indications. First of all, in the discussion about which part of the system needs to be flexible, robust or resilient, it is of utmost important to specify the boundaries of the system. This is very relevant to the case of multifunctional flood defences. Depending on what the system components are, different possibilities for improving the capacity of the system to handle uncertainty can be developed. Second, acknowledging that there is a one-to-one relation between the enabling mechanisms and any of the resilience, system robustness and flexibility approaches, it is required to make clear which mechanism is used to enable which approach and how that specific mechanism enables the intended response to uncertainty. Third, the term ‘robust outcome’ is an umbrella concept that can be used to address any of the flexible, resilience, and system robustness approaches. Herein, the term ‘robust outcome’ has a similar meaning to the term ‘robust decision making’. Both represent a criterion to choose among the various options developed for handling uncertainty, but are not a system design attributes. In short, in the use of these three concepts or combination of them to any domain, the first step should be to clearly specify the meaning of the applied concept in that domain.

3.3 The specific objectives and questions

The case study observations of Chapter 2 demonstrated that flexibility can be an advantageous system capability. It was seen that the presence of flexibility in system design can facilitate the ease of system modification to accommodate changing conditions (e.g. the case of highway on Afsluitdijk). On the other hand, a lack of flexibility makes it difficult to handle change by impeding the ease of system adjustments (e.g. the case of algae bloom in the Grevelingen Lake). Nonetheless, except in the case of Vlissingen, where flexibility is deliberately embedded in the design of the high rise buildings to facilitate future dike reinforcement, the ex-ante discussion of flexibility has not been explicitly addressed in the other three cases.

Apart from the case study observations, there is a growing number of scholars addressing flexibility as an advantageous attribute of systems working under uncertainty. For example, Tsegaye (2013), Huang (2011), Buurman and Babovic (2016), and Gersonius et al. (2015) demonstrate the value of embedding flexibility in the design of urban drainage systems, Jeuland and Whittington (2014) and Anda et al. (2009) discuss the benefit of flexibility for water management under uncertainty, Zhao and Tseng (2003), Ajah and Herder (2005), Juozapaitis et al. (2013) are among the scholars who show the added value of flexible design infrastructure.

In flood risk management, the staged development of flood defences is commonly addressed as a way to increase the flexibility of flood defence systems to handle climate change uncertainty (Manocha and Babovic, 2016, Setiawan, 2016, Kontogianni et al., 2014, Hallegatte et al., 2012, Scandizzo, 2011, Dobes, 2009). It is generally shown that enabling the staged development (and/or staged reinforcement) of flood defences is advantageous though the results are context based and sensitive to the underlying assumptions (Linquiti and Vonortas, 2012, Woodward, 2012). Almost all such literature focuses on valuing flexibility for mono-functional flood defences. Herein, a mono-functional flood defence represents a hard physical structure constructed for retaining high water levels, where there is no other non-water retaining object in the flood protection zone of the defence. Since there is no extra structure around the flood defence that can impede the practice of reinforcement, it can be easily reinforced whenever required.

Taking into account the potential advantage of flexibility and considering the limitations of previous studies, the main objective of this research is formulated as (in Chapter 1) to systematically explore different aspects related to incorporating flexibility in the design and management of multifunctional flood defences. Indeed, proper treatment of flexibility requires supplementary approaches that can help designers and decision makers to identify the options for increasing system flexibility and to evaluate them (Saleh et al., 2003). Accordingly, three specific objectives are defined to be addressed in this research.

3.3.1 Objective 1: conceptualising flexibility

Flexibility is being increasingly viewed as an important system attribute to cope with uncertainty and change (Fankhauser et al., 1999, Linquiti and Vonortas, 2012, Gersonius et al., 2015). Despite the frequent use of the term 'flexibility' in the flood risk management literature (Klein et al., 1999, Morris et al., 2007, Tol et al., 2008, Van Buuren et al., 2013, Felgenhauer and Webster, 2014, Gersonius et al., 2013, Manocha and Babovic, 2016), flexibility is still a vague concept that has been framed in many different ways.

In contrast to the flood risk management literature, several approaches for defining, measuring and valuing flexibility have been explored in other fields such as in manufacturing (Gunderson, 1999, Colombo and Byer, 2012, Upton, 1994, Gupta and Buzacott, 1989, Angkiriwang et al., 2014, Alexopoulos et al., 2010, Boyle, 2006) and in finance (Trigeorgis, 1993, Amram and Kulatilaka, 1998, Latimore, 2002, Hilhorst, 2008, Guthrie, 2009). Although fundamental insights about the concept of flexibility in terms of its definition, measurement, and evaluation are in more advanced stages in other fields, flexibility is still an ill-defined concept.

Perhaps, one reason for the vagueness surrounding the concept of flexibility is that it represents a broad concept which is either understood intuitively in the literature or has varying meaning from context to context and from author to author (Hahn, 1990, Sawhney, 2006, Pérez Pérez et al., 2016, Ryan et al., 2013). For example, flexibility has been viewed and studied as a physical property of a system design (Ryan et al., 2013, Saleh et al., 2003), as an attribute of decision making (Benjaafar et al., 1995, Kandemir and Acur, 2012), as an economic indicator (McGrath et al., 2004, Bastian-Pinto et al., 2009), and as a strategic tool (Fraser, 2016, Mason and Nair, 2013). As argued by Shewchuk and Moodie (1998), Shi and Daniels (2003) and Jain et al. (2013), the perception of and the level of deliberation on flexibility depends on the perspectives of the authors as to what constitutes their system under study and its environment.

Generally, it can be seen that the insights provided in the literature on manufacturing and supply chain flexibility have supported the definition and measurements of flexibility in various areas such as in aerospace (Nilchiani, 2005, Saleh et al., 2009), information technology (Golden and Powell, 2000, Zhao et al., 2016), e-business (Soffer, 2005) and urban drainage system design (Eckart, 2012, Spiller et al., 2015). Today, the insights of such other disciplines have not been applied to (multifunctional) flood defence design and management.

Due to the context-based nature of the flexibility concept and the complexities involved in the design and management of multifunctional flood defences, there is a need to clarify flexibility before using it in this context. Accordingly, it is the first objective of this research to structure the discussion of flexibility by conceptualising flexibility in the context of multifunctional flood defences. Hence, the question to be answered in this regard is:

1) What is flexibility and how to characterise and define it in the context of multifunctional flood defences?

3.3.2 Objective 2: functional modelling and performance analysis

During the study to answer the first research question, it was apparent that the required flexibility for a multifunctional flood defence cannot be holistically determined without addressing the interactions between the components of a multifunctional flood defence. Furthermore, the case study observations of Chapter 2 demonstrated that the functional components of a multifunctional flood defence and its external environment interact in very dynamic, complex and non-linear ways. When flexibility is aimed at maintaining the desired performance of a multifunctional flood defence, better understanding of these interactions, which can impact the system performance, would be crucial to the process of identifying and evaluating flexibility.

In most cases, a flood defence, and particularly a dike, is perceived as a physical entity which works independently of human actions. The role of human actions on dike performance should not be underestimated in the case of multifunctional flood defences, where one or more (human operated) secondary object(s) exist in the vicinity of the dike body. It has already been observed in the case studies of Chapter 2 that human actions/decisions are the major drivers of change in human artefacts, such as multifunctional flood defences. These actions can impact the system's performance positively (e.g. preventing and alleviating a failure) or negatively (e.g. causing performance deficiency). In the process of identifying the ways of including flexibility in multifunctional flood defence systems, exploring both the positive and negative impacts of human actions can provide valuable information for planning to dampen and/or benefit from the interactions between the technical components of the system, human actions and the environment.

Traditionally, reliability analysis methods are used for the design and assessment of flood defences (Voortman, 2003, Van Gelder et al., 2009, Buijs et al., 2009). Reliability is quantification of the probability of failure-free performance of a flood defence over a specified timeframe and under specified environmental conditions (Buijs et al., 2007). The premise of conventional reliability analysis is that the nature of system behaviour is stochastic and that system performance can be explained by decomposing the system into independent components (Bier et al., 1999, Pollack, 2007, Rouse and Serban, 2011, Mai et al., 2008). It is, however, well-known in the literature that as the relationships between system components become more complex, conventional reliability analysis methods become less adequate to address the whole spectrum of opportunities and threats associated with the interactions within the system (Rasmussen, 1997, Baxter and Sommerville, 2011).

Taking into account the complexities of the relationships caused by the multifunctional use of flood defences, there is a need for a complementary method for performance analysis of multifunctional flood defences. Accordingly, the second objective of this research is to develop such a method for performance analysis of multifunctional flood defences. The intention is that the method is used to identify the positive and negative risks associated with these dependencies in order to improve the system capability to mitigate the resulting threats and to take advantage of the opportunities created. Therefore, the associated second question of the research is:

2) How to model the functional performance of a multifunctional flood defence in order to devise strategies for maintaining the desired performance of the system under uncertainty?

3.3.3 Objective 3: Valuing flexibility

In Chapters 4 & 5, flexibility is generally perceived as an advantageous system attribute. A comprehensive treatment of the issue of flexibility should also address whether it is valuable to incorporate flexibility in the design and management of multifunctional flood defences.

The case studies of Chapters 4 & 5 demonstrated that flexibility is a multidimensional concept which can be achieved in many different ways. One such way is through the specification of the design lifetime (Saleh et al., 2004). In this research, design lifetime indicates the time period (or the time-step) between two reinforcement practices. In the presence of uncertainty (i.e. sea level rise uncertainty in this research), determining proper reinforcement intervals presents a challenge to flood defence designers and decision makers. While constantly reinforcing the flood defences is not a feasible choice, one-time reinforcement is also not effective in handling future changes.

Staged development of flood defences is proposed in the flood risk management literature, as a way of increasing flexibility in reinforcement decision making (Gersonius et al., 2015, Gersonius et al., 2011, Dobes, 2009, Scandizzo, 2011). The ability to revise investment decisions based on the arrival of new information in the future makes the embedded flexibility a valuable attribute of a strategy. This ability to modify investment decisions is referred to as 'managerial flexibility' (Triantis, 2003).

Different evaluation models are proposed in the literature for assessing the value of managerial flexibility. These models are often used to assess the economic benefits of enabling flood defence reinforcement in pre-defined time-steps (or using fixed design lifetimes). Another way of increasing managerial flexibility is the use of varying design lifetimes (not pre-specified time-steps). The economic benefits of enabling reinforcement at any time, by allowing for variable design lifetimes, has been only limitedly reported in the literature (Linquiti and Vonortas, 2012, Hoekstra and Kok, 2008).

Previous work on flexibility assessment has only been focused on valuing flexibility for mono-functional flood defences. Generally speaking, it is expected that the multifunctional use of flood defences increases the difficulty of dike reinforcement. This is due to the presence of one or more secondary structures in the vicinity of the flood defence that do not allow for a simple widening and heightening of a dike. It is therefore needed to explore whether increasing managerial flexibility in reinforcement decision making will be valuable in the context of multifunctional flood defences. Accordingly, the third objective of this research is to assess the value of managerial flexibility embedded in reinforcement decision making of multifunctional flood defences in the Netherlands. Therefore, the third question of research is:

3) To what extent does an increase of the managerial flexibility improve the lifecycle cost-effectiveness of reinforcement of multifunctional flood defences?

3.4 Research set-up

This dissertation contains eight chapters. The outline of the dissertation is shown in Figure 1 in Chapter 1. So far,

Chapter 1 introduces the research background, problem of research, the main objective and the outline of the dissertation.

Chapter 2 presents a case study of evolution of four multifunctional flood defences in the Netherlands.

Chapter 3 reviews the published literature on handling uncertainty in flood risk management. The insights gained from the case studies and literature review are used to specify the three objectives of this research.

The next chapters (4, 5 & 6) of the dissertation present the research conducted to address the three research questions, as follows.

In Chapter 4, the relevant literature on the concept of flexibility from various domains is studied and discussed. The intention is to gain an understanding of the diverse interpretations and definitions of flexibility presented in the literature from different domains. Thereafter, a framework for conceptualising flexibility and its working definition is developed. The potential of the framework is then examined in a case study of a multifunctional flood defence.

In Chapter 5, following the specific understanding of flexibility, as presented in Chapter 4, a further literature study is conducted on the methods that can be used for performance analysis of complex systems. Afterwards, an approach for functional modelling and (qualitative) risk analysis of multifunctional flood defences is developed, based on the 'Functional Resonance Analysis (FRAM)' developed by Hollnagel (2012). The proposed method is examined to compare the performance of four alternative designs of a multifunctional flood defence, based on a case from the Dutch coastal town of Katwijk.

In Chapter 6, a cost-effectiveness analysis is conducted to assess the value of increasing managerial flexibility in reinforcement decision making. A cost function that has been initially developed by Kind (2011) and applied in De Grave and Baarse (2011) is adopted to assess the lifecycle cost of each reinforcement strategy. The evaluation model of this chapter is examined in eight cases of mono-/multifunctional flood defences in coastal areas of the Netherlands.

The dissertation ends in Chapter 7 & 8 by discussing the results of the research, recommendations for future work and reflecting on the research outcome.

Chapter 7 answers the research questions based on the research results presented in Chapters 4, 5 and 6. The limitations and implications of the research are also discussed in this chapter.

Chapter 8 is the closing chapter of this dissertation. This chapter begins by providing a few recommendations for future research based on the research results. The chapter ends by proposing some challenges in handling uncertainty and change that have not been addressed in this dissertation.

The body of the dissertation consists of two published and one accepted journal papers. Each paper has been prepared with the intention of being self-contained, so as to be independent of the other papers. As a result, there is some overlap in content between the various papers and chapters, particularly regarding the introductory parts of the papers.

4 Understanding flexibility for multifunctional flood defences: a conceptual framework[1]

"Take up one idea. Make that one idea your life – think of it, dream of it, live on that idea. Let the brain, muscles, nerves, every part of your body, be full of that idea, and just leave every other idea alone. This is the way to success."

Swami Vivekenanda

4.1 Introduction

The Netherlands is a flood-prone, lowland country located in the delta of four large rivers, along the North Sea. At present, eight million people live in the embanked areas, where roughly 65% of the country's gross national product is generated (Kabat et al. 2009). The threat of flooding is, however, subject to change. On the one hand, natural environmental changes (e.g. sea level rise and land subsidence) pose changes in the frequency and severity of extreme events. On the other hand, continuous land use alteration and economic development influence the exposure of impacted people and valuable assets (Djordjević et al., 2011). In such a dynamic situation, preserving the safety and prosperity of the embanked areas require persistent investment in maintenance and reinforcement of flood defences (Stive et al., 2011).

[1] Chapter is based on: Anvarifar, F., Zevenbergen, C., Thissen, W., & Islam, T. (2016). Understanding flexibility for multifunctional flood defences: a conceptual framework. Journal of Water and Climate Change, 7(3), 467-484.

Reinforcement of flood defences often requires space, which is scarce in the densely populated regions. The competing needs of housing, commerce, transportation, and agriculture have to fit in a relatively small surface area. Simultaneously, the safety of the living environment and the quality of the landscape has to be maintained (Ligtvoet et al., 2009). One strategy to address this issue can be by co-locating several activities in the available space (Woltjer and Niels, 2007). This can be achieved by integrating urban functions into the flood defences, and is referred to as multifunctional flood defences (Van Loon-Steensma and Vellinga, 2014). Multifunctional use of flood defences can increase the synergy between reinforcement and urban development by maintaining sufficient safety and enhancing the quality of the living environments along with having a lower total land requirement (Tettero, 2013, Stalenberg, 2010).

The resulting artefacts are long-lived, capital intensive and irreversible investment interventions. The performance requirements for these artefacts can vary considerably due to socio-economic developments, technological evolutions and natural environmental changes. Since choices made today will influence those of tomorrow, inflexibility can lead to inadequate system performance with unnecessary capital and operational costs or the need for expensive system upgrades to meet the future requirements (Ajah, 2009). Conversely, flexibility is a desirable feature that can enhance the system capabilities and functionality (Schulz et al., 2000), and lessen the effects of erroneous decisions throughout the entire life-cycle (Gersonius et al., 2013).

The use of flexibility in water management, for coping with extreme events, is not a new topic of discussion (Gunderson, 1999, Olsson, 2004, Colombo and Byer, 2012). It has been long realised that the deterministic and probabilistic forecasts of extreme events based on historical records do not provide sufficiently valid information for decision-making (Milly et al., 2007). Furthermore, uncertainties about climate change impacts, and socio-economic developments do not allow for precise quantification of potential damages caused by weather extremes (Tol, 2005). Lack of definite information motivates the shift from a 'predict and control regime' to a more flexible management approach based on learning over time (Pahl-Wostl, 2008). In this regard, flexibility is generally perceived as positive, valuable, and advantageous to have, though there are limited publications that focus on identifying and evaluating it in the field of water management (Fankhauser et al., 1999, Linquiti and

Vonortas, 2012, DiFrancesco and Tullos, 2014b). Concurrently, there exists no generally accepted characterization and definition of flexibility throughout the literature.

It is the purpose of the present paper to develop a conceptual framework to clarify the concept. This study is seen only as the first step in the process of developing a methodology for identifying and evaluating flexibility in the design and management of multifunctional flood defences. The research method follows a positivistic approach (Lin, 1998, Warfield, 2005) and focuses on a theoretically based identification of the commonalities that hold across different fields in order to be used as the building blocks of proposed conceptual framework of the study. The paper is divided into three major parts as explained below.

First, the concept and usage of flexibility is reviewed as presented in a variety of literature. Over three hundred worldwide academic publications have been explored initially. The selection of the literature began with Seebacher and Winkler (2013), who have conducted a citation analysis of flexibility literature in manufacturing, and was extended by using a Google Scholar search on a wide range of flexibility-related keywords.

Second, the conceptual framework of the study is proposed in the form of four self-consistent and step-wise questions. The questions are adapted from Upton (1994) and address the commonalities found in the literature. A selection of thirty-five publications is then synthesized to distil the eight characteristic features of flexibility, in association with the proposed questions. Subsequently, a working definition of flexibility is proposed as well.

And third, an illustrative case study follows to demonstrate application and potential of the framework in discussing, identifying, and evaluating flexibility for the development of a multifunctional flood defence. The paper ends with some challenges and recommendations for future research.

4.2 Flexibility in the literature

A necessary step for better understanding of flexibility in the context of multifunctional flood defences is to remove the ambiguity and vagueness of the concept. Indeed, much can be done by investigating the insights presented in the literature. Flexibility is a topic of interest and discussion in various fields, such as product and organizational design (Sanchez and Mahoney, 1996, Kandemir and Acur, 2012, Singh et al., 2013, Kok and Ligthart, 2014), information technology (Byrd and Turner, 2000, Highsmith, 2013, Nanath and Pillai, 2014), business development (Bryson et al., 1993, Regev et al., 2006, Arnold and Artz, 2015), infrastructure development (Zhao and Tseng, 2003, De Haan et al., 2011, Gil and Biesek, 2014), adaptation to climate change (Smit and Pilifosova, 2003, Few et al., 2004, Adger et al., 2005, Heller and Zavaleta, 2009) and complex systems (Ethiraj and Levinthal, 2004, Alkemade et al., 2009, Moses, 2010).

The literature review of this study is, however, limited to three areas of investigation. The field of flood management is chosen because it is the primary field of interest. Moreover, during the initial investigation of the worldwide literature on the web, it was observed that the generic principles of flexibility as presented in the real options and manufacturing publications have provided the foundation for conceptualizing and operationalizing flexibility in various fields such as aerospace systems (Galbraith, 1990, Saleh et al., 2003, Nilchiani, 2005) information technology (Duncan, 1995, Panayi and Trigeorgis, 1998, Dorsch, 2015), infrastructure planning (Ajah, 2009, De Neufville and Scholtes, 2011), port development (Mansouri et al. 2010; Taneja et al. 2014), water supply and waste water systems (Spiller et al., 2015, Zhang and Babovic, 2012), emergency management (Ward et al. 2015) and urban planning (Macintosh, 2013, Geltner and De Neufville, 2012). Hence, it was assumed that the insights offered by real options and manufacturing publications may also provide sufficient coverage for understanding flexibility for multifunctional flood defences.

This section aims to present the varied conceptual usage of flexibility as discussed in the literature. The multi-disciplinary literature review of the concept of flexibility is not meant to be exhaustive. Rather, the chosen publications are considered to represent significant contributions to a wide body of knowledge about flexibility in the areas under consideration. The end-goal is to derive the major themes and limitations within each context, and the commonalities and inconsistencies across the flood management, real options, and manufacturing literature.

4.2.1 Flexibility in the flood management literature

The changing threat of flooding is a major concern for the development of flood protection measures (Downtown et al., 2005). Climate change is expected to alter the frequency and severity of extreme events (IPCC, 2007), which is of particular relevance for flooding (Djordjević et al., 2011). Demographic and economic developments in floodplains are among the non-climatic factors affecting the impacts of floods (Nicholls, 2004). Climatic and non-climatic changes are interlinked (Zevenbergen et al., 2008), and non-stationary in their nature (Gersonius et al., 2013). Consequently, not only the magnitude and speed of changes in flood hazard, but also the extent of the consequences of flooding are deeply uncertain and unpredictable (Rahman et al., 2008).

Provision of sufficient safety in such a dynamic environment is a dilemma. On the one hand, flood defences are 'quasi-irreversible' (Fankhauser et al., 1999) investment interventions that cannot be easily upgraded. On the other hand, the performance requirements are expected to change in accordance with the environmental changes. In anticipation of change, consideration of flexibility in design and management of flood protection measures is increasingly recommended in the literature (Nicholls and Branson, 1998, Adger et al., 2005, Gersonius et al., 2011, Woodward et al., 2013). Achieving flexibility proactively is expected to be cheaper than reacting to change after the occurrence (Stern, 2006, Tol et al., 2008). Moreover, enhancing the flexibility can ensure proper performance of flood defences under a wide range of plausible future conditions (Smit et al., 2007).

A commonly cited approach for achieving flexibility for a typical flood defence is by allowing for mid-term adjustments and modifications of the structure according to the new insights gained over time (Klein et al., 1999, Morris et al., 2007, Tol et al., 2008, Van Buuren et al., 2013). The investment 'options' are left open for future adaptation (Haasnoot et al., 2012), and are postponed until the time that the costs of further delay are greater than the benefits (Felgenhauer and Webster, 2013). Several studies have shown the added value of embedding investment timing flexibility through application of real options techniques (Dobes, 2009, Linquiti and Vonortas, 2012, Scandizzo, 2011, Woodward et al., 2011, Jeuland and Whittington, 2014).

4.2.2 Flexibility in the real option literature

A growing body of literature discusses the value of incorporating real options in the long term development planning for capital intensive projects under market uncertainty. The term 'real option' was first used by Myers (1977) referring to the 'right, but not an obligation' to modify the system under consideration to adapt to its changing environment (Cardin and De Neufville, 2008). Having the right to revise the decisions on a predetermined cost and at any time adds value to the option and makes it distinctive from an 'alternative' or 'choice' (De

Neufville, 2002). The option pricing techniques are used to compare the costs of delaying decisions and acquiring flexibility with the benefits of waiting (Scandizzo, 2011).

Various types of real options - such as the option to defer, stage, expand the investment - have been proposed in the literature (Amram and Kulatilaka, 1999, Trigeorgis, 2005). The options are aimed to provide flexibility for hedging against negative impacts of uncertainties and taking advantage of unexpected upside opportunities created in the future (De Neufville and Scholtes, 2011). Each option demonstrates a managerial decision or action that can be taken in response to the changes in the market. Management plans are considered flexible if they can be delayed and updated periodically and proactively (Luehrman, 1998).

The focus of the options thinking approach is on measuring the financial value of embedding managerial flexibility. The method is limited to market uncertainty as the only source of uncertainty. However, the proposed options are comprehensive and can be used in various investment projects. The different aspects of flexibility are only partially discussed.

4.2.3 Flexibility in the manufacturing

There exist a large number of publications discussing flexibility in manufacturing (Slack, 1983, Gupta and Goyal, 1989, Mandelbaum and Buzacott, 1990, Koste and Malhotra, 1999, Duclos et al., 2003). The need for flexibility in manufacturing is related to the complexities created by technological advancements, rapidly changing business environment, constant pressure to upgrade the products, and satisfying customers' preferences (King and Sivaloganathan, 1999, Rajan et al., 2005, Shi and Daniels, 2003). In response, flexibility is aimed at demand management, shortening the lead times (Slack, 1983), 'quickness of response' (Fisher et al., 1994), and 'responsiveness' (Holweg, 2005). Flexibility is generally understood as the system capability to be reconfigured in order to hedge against uncertainty (Van Mieghem, 1998, Goyal and Netessine, 2007), and to maintain profitability and competitiveness (ZelenoviĆ, 1982) in a cost efficient way (Duclos et al., 2003).

Since different uncertainties exist, various types of flexibility have been identified and discussed within the published literature. They vary from adjustments in system components (e.g. labour, material, machine), organization (e.g. procedure, processes, volume), products (e.g. production, market), and distributions (e.g. responsiveness, network) as identified by several scholars such as Browne et al. (1984), Gerwin (1993), and (Duclos et al., 2003).

However, the types of flexibility have been interpreted differently by different scholars (Seebacher and Winkler, 2013). The differences are influenced by the context of the system (De Toni and Tonchia, 1998), multiplicity of variables (Kersten et al., 2011), and multidimensional nature of flexibility (Sethi and Sethi, 1990).

Subsequently, different logics have been used for classifying the growing number of flexibility types into different dimensions. For example, Bernardes and Hanna (2009) and Eppink (1978) use the nature of uncertainty and predictability to classify flexibility into reactive (passive) or proactive (active) responses; ZelenoviĆ (1982) was one of the first who characterized flexibility based on the time frame dimension of change into operational, tactical, and strategic; Upton (1994) used the dimensions of 'internal' and 'external' flexibility based on the intention of flexibility to accommodate competitiveness via internal capabilities of a manufacturing unit ('what we can do') or adjusting to the external advantages derived from it ('what the customer sees'). However, manufacturing literature provides a broad view of the flexibility concept. There is no general agreement on definition and characterization of flexibility within the field. Moreover, they represent fairly unstructured and fragmented classification schemes that are complex and needs to be adjusted to the context under consideration (Upton, 1994, Winkler and Seebacher, 2012).

Concluding from the literature review of the prior fields of inquiry, it appears that there are some commonalities in the use of flexibility across the literature while there are inconsistencies in characterizing them, even within the same discipline. First, throughout the literature, the need for flexibility is related to changing circumstances though the nature of change and degree of uncertainty about the change vary by context. Second, flexibility is seen as advantageous and desirable attribute capable of handling uncertainty and change. However, the preferred goal and the capabilities of flexibility in achieving them are specified differently based on the context of the problems faced in each field of investigation. Third, flexibility often entails a kind of response to uncertainty and change, although what characterises the response is described by disparate dimensions depending on the nature of change and context of the system under consideration. Fourth, each discipline proposes some ways of achieving flexibility. However, they differ widely in relation to the nature of change and uncertainties and their impacts. Overall, the observed commonalities demonstrate consistency in conceptualising flexibility across the literature. However, the field specific, and context based characterization of these common aspects create the sources of inconsistency and ambiguity across, and within the disciplines.

4.3 The conceptual framework & definition of flexibility

The literature review has demonstrated that while the conceptualization and operationalization of flexibility is more advanced in the context of real options and manufacturing, in the field of flood management, the concept needs to be enriched. To do so, this section proposes a conceptual framework, as defined by Maxwell (2005), to be used to clarify the concept and structure the discussion of flexibility in the context of multifunctional flood defences. The research adopts the stance of positivistic approach (Lin, 1998, Warfield, 2005) in which the framework is built based on the observed commonalities the literature. Such an approach has been similarly applied by many scholars such as Taljaard et al. (2011), in the context of integrated coastal management, and Nilchiani (2005), in the context of aerospace engineering. Both studies have used the commonalities in the literature for developing their proposed frameworks.

In the first step, the observed commonalities in the use of flexibility across the literature are presented in the form of four, step-wise, and self-consistent questions as presented below. The questions are adapted from Upton (1994), though the intended meaning of the dimensions of flexibility in Q3 is not the same as stated by him. Rather, this research uses the word dimension as applied by Evans (1991) and Golden and Powell (1999), which supports the intention of this research.

Q1- Why is flexibility needed? This question establishes the motivation for consideration of flexibility.

Q2- What is it that flexibility is required for? This question seeks to describe the competences of the flexibility concept.

Q3- What are the dimensions of flexibility? This question indicates the extent within which flexibility can be achieved.

Q4 -What needs to change or be adapted? This question discusses the potential ways of achieving flexibility.

Each question of the framework addresses one of the common aspects of flexibility derived from the literature. Since, the common aspects are consistent across the fields; they are assumed to be instrumental for structuring the discussion of flexibility for multifunctional flood defence development as well.

However, the four questions help to draw the spectrum of the areas that needs to be considered in discussing flexibility. The observed sources of ambiguity stem from inconsistency in characterizing flexibility across the literature. In order to provide greater clarity and to answer the questions without confusion in the context of multifunctional flood defence, the characteristic features of flexibility associated with each question need to be clearly specified.

The review of over three-hundred flexibility-related publications demonstrated that the majority of the publications are focused on operationalizing and implementing (Boyle, 2006, Ewert et al., 2009, Hallegatte, 2009, D'Angelo et al., 2013, Filatova, 2014), measuring (Ramasesh and Jayakumar, 1991, Dixon, 1992, Georgoulias et al., 2007, Moon et al., 2012), and evaluating (Ito, 1987, Cortazar et al., 1988, Kulatilaka, 1988, Chod et al., 2012, Christopher and Holweg, 2011, Linquiti and Vonortas, 2012) flexibility. This section selects and synthesizes thrifty-five papers that focus on presenting a self-definition of flexibility, developing distinguishable characteristic features of flexibility, and/or presenting a thorough review of the preceding publications in the field.

A best-fit approach (Bond, 1994) is taken to distil the characteristic features of flexibility. The attempt is to select the characteristic features that are meaningful in both real options and manufacturing contexts. Correspondingly, the case specific characteristic features are omitted. Hence, the chosen characteristic features are assumed to be context-independent. This assumption follows the analysis strategy outlined by Bond (1994) and Shackelford et al. (2005).

Table 2, summarises the four questions of the framework, their associated characteristic features, and the spans of the terms used for searching the references. It was attempted to search each reference for explicit use of the stated terms, though in some cases, in particular relevant to the second and fourth questions (Q2 & Q4), the intent has been inferred based on the implicit evidences presented in the authors' work.

Table 2, the four questions of the framework, their associated characteristics features of flexibility and their spans

Questions	Characteristic feature	Span of the characteristics feature
Q1- Why is flexibility needed?	(e) Change	Internal and external
	(f) Uncertainty	Unforeseeable, unpredictable, unplanned or uncertain
Q2 –What is that flexibility is required for?	(g) Goal	Handling both downsides and upsides of uncertainty and change
	(h) Capabilities	Range/ number of options and ease of transition (time, cost, performance losses
Q3- What are the dimensions of flexibility?	(e) Temporal	Strategic, tactical, and operational
	(f) Mode of response	Proactive (offensive) and reactive (defensive)
Q4 -What needs to change or be adapted?	(g) Types	Managerial actions or decisions
	(h) Enablers	Sources of flexibility in technical design

The characteristics features associated with each question and their spans are detailed in following. The distribution of the eight characteristics features as applied by the scholars in the fields of real options, and manufacturing is depicted in Tables 3 & 4.

Table 3, synthesized literature from the field of real options *

	Q1		Q2		Q3		Q4	
Source	a	b	c	d	e	f	g	h
(Myers, 1977)		x	x				x	
(Amram and Kulatilaka, 1999)		x	x				x	
(Triantis, 2003)		x	x		x		x	
(De Neufville, 2004b)		x	x		x	x	x	
(Trigeorgis, 2005)		x	x				x	
(Wang and De Neufville, 2006)		x	x				x	x
(Cardin and De Neufville, 2008)			x				x	x
(Mikaelian et al., 2011)		x	x				x	x
(Cardin, 2014)		x	x	x			x	

Table 4, synthesized literature from the field of manufacturing *

	Q1		Q2		Q3		Q4	
Source	a	b	c	d	e	f	g	h
(Eppink, 1978)		x	x		x	x	x	x
(ZelenoviĆ, 1982)		x	x				x	x
(Slack, 1983)		x		x			x	x
(Gupta and Goyal, 1989)	x	x		x			x	x
(Mandelbaum and Buzacott, 1990)	x	x		x			x	
(Sethi and Sethi, 1990)	x	x	x			x	x	x
(Evans, 1991)	x	x	x	x			x	x
(Gerwin, 1993)		x	x	x	x		x	x
(Upton, 1994)		x		x	x	x	x	x
(Correa and Slack, 1996)	x	x	x	x			x	x
(Volberda, 1996)		x	x	x	x		x	x
(De Toni and Tonchia, 1998)		x		x	x	x	x	x
(Van Hoek, 1999)		x			x	x	x	x
(Golden and Powell, 1999)		x	x	x	x		x	
(Koste and Malhotra, 1999)		x		x	x	x	x	x
(Beach et al., 2000)	x	x		x	x	x	x	x
(Duclos et al., 2003)		x	x	x			x	x
(Sánchez and Pérez, 2005)		x	x	x		x	x	x
(Stevenson and Spring, 2007)		x		x	x	x	x	x
(Buzacott and Mandelbaum, 2008)	x	x	x				x	x
(Bernardes and Hanna, 2009)		x		x	x		x	x
(Filho et al., 2012)	x	x	x		x	x	x	x
(Winkler and Seebacher, 2012)	x	x		x	x		x	x
(Jain et al., 2013)	x	x			x	x	x	x
(Roberts and Stockport, 2014)	x	x	x		x		x	
(Angkiriwang et al., 2014)	x	x	x		x		x	x

* In each Table, Q1, Q2, Q3, & Q4 refer to the four questions of the framework. The letters (a) to (h) demonstrate the eight characteristics features of flexibility as: Change (a); Uncertainty (b); Goal (c); Capabilities (d); Mode of response (e); Temporal (f); Types (g); Enablers (h). The spans of the terms searched for each column are shown in Table 2.

Q1- Why is flexibility needed?

The common ground on which all the authors agree is the inevitability of change in the system itself and of its environment over time (ZelenoviĆ, 1982, Golden and Powell, 1999, Stevenson and Spring, 2007). The degree of change can vary from being planned and predictable to deeply uncertain and unplanned. Both the change and uncertainty are used to characterize the need for flexibility in the literature, and are adopted in the current paper.

Sources of change can be internal or external to the system boundary (De Toni and Tonchia, 1998, Van Hoek, 1999, Beach et al., 2000). As appeared in real options and manufacturing literature, the major sources of external changes are mentioned to be variations in entities such as customers, suppliers, market, and technologies (Myers, 1977, ZelenoviĆ, 1982, Gerwin, 1993, Duclos et al., 2003, De Neufville, 2004b). On the other hand, machine breakdowns, variability in processing times, and quality problems exemplify the internal sources of change in manufacturing (Gupta and Goyal, 1989, Buzacott and Mandelbaum, 2008). Twelfth authors have addressed both internal and external sources of change that have a need for flexibility.

Lack of knowledge about change specifications results in admitting uncertainty (Nilchiani and Hastings, 2007). All of the authors have mentioned flexibility for dealing with the uncertainty associated with a source of change. In addition to explicit use of the term uncertainty, the other terms which have been used by the authors to explain uncertainty include ‘unforeseen’ (Golden and Powell, 1999, Roberts and Stockport, 2014), ‘unpredictable’ (Gupta and Goyal, 1989, Angkiriwang et al., 2014), and ‘unplanned’ (Correa and Slack, 1996) changes. However, manufacturing literature consider flexibility for handling both types of predictable and unpredictable changes (Beach et al., 2000, Golden and Powell, 1999). The real options literature claim that as uncertainty grows, flexibility becomes more valuable (Cardin and De Neufville, 2008, Triantis, 2003). Here in this paper, in addition to the change, uncertainty is the second characteristic feature that is adopted for discussing the need for flexibility.

Q2- What is it that flexibility is required for?

Here the primary attempt is made at establishing what will be offered by taking flexibility into account. This can be described by two characteristics features of goal and capabilities of flexibility. The former demonstrates the desired end result of having flexibility whilst the later demonstrate the abilities of flexibility to achieve its goal.

Flexibility is aimed in the literature at handling both downside and upside of uncertainty and change. The manufacturing literature represents an explicit focus on maintaining and enhancing competitiveness and profitability in a cost-effective way (Mandelbaum and Buzacott, 1990, Bernardes and Hanna, 2009, Jain et al., 2013), which is more prone to make benefit of uncertainty and change. Handling the negative consequences of uncertainty and change has also been mentioned by many authors implicitly or explicitly (Eppink, 1978, Sethi and Sethi, 1990, Filho et al., 2012). In the real options literature, flexibility is clearly aimed at both capitalizing favourable future investment opportunities and hedging the risks by all the authors (for example, Cardin, 2014, Wang and De Neufville, 2006). There are totally twenty-third authors who have addressed flexibility for coping with both downsides and upsides of uncertainty and change implicitly or explicitly.

Flexibility is often qualified based on the capabilities offered by the consideration of flexibility (Gupta and Goyal, 1989). Capabilities of flexibility can be described in terms of 'scope' and 'achievability' (Bernardes and Hanna, 2009). The scope refers to the total number and range of options the system can accomplish whilst options are held in reserve to meet the future needs (Slack, 1983, Mandelbaum and Buzacott, 1990, Gerwin, 1993, Volberda, 1996). Achievability denotes the 'ease' of transition (Sánchez and Pérez, 2005), transition 'penalties' (Upton, 1994), or 'mobility' in terms of cost, time, or performance losses (Koste and Malhotra, 1999) for attaining each option within the scope. The quantified capabilities of flexibility are used as indicators of cost-effectiveness, and efficiency of flexibility consideration (Slack, 1983, Gerwin, 1993, Gupta and Buzacott, 1989, Beach et al., 2000). Furthermore, there are eighteen authors who have addressed both the scope and achievability as defined here, in an implied manner.

This study chooses the characteristic feature of 'goal' of flexibility to not only reduce the downside losses and vulnerabilities, but also to exploit the upside opportunities created in the future. Besides that, the selected characteristic feature of 'capabilities' involves both the scope (the range/number of options that can be achieved) and the achievability (the transition time, cost, and performance losses) for qualifying flexibility.

Q3- What are the dimensions of flexibility?

Flexibility is acknowledged to be multidimensional (Sethi and Sethi, 1990) and polymorphous (Evans, 1991). The literatures on dimensions of flexibility are rather vast and articulated (Seebacher and Winkler, 2013). There is inconsistency in the use of the term dimension even within a single firm (Golden and Powell, 1999). Similar to Evans (1991), and Golden and Powell (1999), the current paper uses the term dimension to indicate the extent within which flexibility can be achieved. Accordingly, the two dimensions of the 'mode of response' and 'temporal' are derived from the literature, which are found to be generic and independent of the context of the system under consideration. Hence, the two of them are chosen for characterising the dimensions of flexibility for the current paper.

The mode of response indicates the standpoint of decision makers towards flexibility based on the effects of change (Golden and Powell, 1999). Defensive mode of response represents a passive reaction to change after the occurrence, and aims at minimizing the negative impacts and losses (Evans, 1991, Gerwin, 1993, Eppink, 1978). It is an event-driven approach, and it is strongly relied on the combined use of control and buffers (Filho et al., 2012). The offensive approach actively monitors the change process and its impacts. The goal is to prevent the negative impacts and take advantage of created opportunities in anticipation of external changes (Gerwin, 1993, Triantis, 2003). The system configuration is then proactively redesigned and altered in anticipation of change (Angkiriwang et al., 2014). The Manufacturing literature makes use of both response types to respond to foreseeable and unforeseeable changes (Eppink, 1978). However, real options literature encompasses various forms of proactive management of uncertainty (De Neufville, 2004b). Sixteen authors have addressed both reactive and proactive modes of response, which are both considered as the components of the characteristic feature of 'mode of response' for the framework of the current paper.

The temporal dimension reflects the period of time over which change will happen (ZelenoviĆ, 1982, De Toni and Tonchia, 1998). The time horizon of change can vary from short term to long term while the frequency of change can be discrete or continuous (Upton, 1994). Three widely established categories of the temporal dimension of flexibility are operational, tactical, and strategic (Eppink, 1978). Operational flexibility entails rapid reaction to short-term, discrete and predictable changes such as machine breakdown or shortage of raw material. It includes a range of operations the system can handle without a major setup (De Toni and Tonchia, 1998, Upton, 1994, Stevenson and Spring, 2007). Tactical flexibility entails occasional system alternation with some effort and commitment. For instance, a major opportunity for improvement without changing the overall system configuration exemplifies tactical flexibility (Upton, 1994, De Neufville, 2004b). Strategic flexibility denotes long-term changes in response to the continually changing environment. It involves dynamic alteration in design, development, and operation of the system (Roberts and Stockport, 2014). However, most of the non-marked authors have addressed the strategic flexibility (for example, Slack, 1983, Amram and Kulatilaka, 1999, Trigeorgis, 2005, Angkiriwang et al., 2014), there are only eleventh authors who have mentioned all the three strategic, operational, and tactical time frames. The three of them are taken into account as the span of the temporal characteristic feature of flexibility in the current paper.

In addition to the dimensions of temporal and mode of response, there are other dimensions of flexibility defined in the literature that are not considered for characterizing flexibility here in this paper. For example, De Toni and Tonchia (1998) propose three dimensions of 'horizontal', 'vertical', and 'by the object of the variation'. The horizontal and vertical dimensions of flexibility refer to the phases of manufacturing and levels of hierarchy in manufacturing operations. The object of variation outlines the location of flexibility in relation to the boundaries of manufacturing. The dimension of 'by the object of the variation', has also been called 'internal' and 'external' flexibility by some authors such as Eppink (1978) and Upton (1994), 'focus' by Golden and Powell (1999). The internal and external flexibility show that flexibility is not confined by organizational boundaries of manufacturing. For example, the trading relationships can extend the flexibility of manufacturing (Golden and Powell, 1999). The dimensions discussed in this paragraph are specific to the nature of manufacturing. Therefore, they are not used to characterise flexibility for the framework of the current paper.

Q4- What needs to change or be adapted?

The last question of the framework looks for the ways of achieving flexibility or the sources of flexibility. Here in this paper, the two characteristics features of flexibility 'types' and 'enablers' are adopted to describe the potential ways of achieving flexibility as defined by Mikaelian et al. (2011) and Cardin (2014).

The approach of real options literature towards determining the ways of achieving flexibility is comprehensive. Basically, the real options refer to a variety of managerial decisions and actions that can be taken to respond to change and uncertainty (Myers, 1977, Triantis, 2003). These managerial options are independent of the context of the system and can be applied for any investment intervention under uncertainty. Often, the conventional real options literature does not address what enables the managerial options. More recently, Mikaelian et al. (2011) and Cardin (2014) have characterised the ways of achieving flexibility into the flexibility 'types' and 'enablers'. The flexibility types or real options 'on' system (Wang and De Neufville, 2006) have the same meaning as the conventional real options. Some examples of these real options are the options to expand, defer, and shrink the investment (Trigeorgis, 2005). Flexibility enablers are also called 'design flexibility' (Saleh et al., 2003), flexibility 'in' the project (Wang and De Neufville, 2006), and flexibility 'mechanism' (Mikaelian et al., 2011). Flexibility enablers refer to the sources of alterations in the technical design of a system to make it changeable, and are determined based on the nature and effects of uncertainty and change (Cardin and De Neufville, 2008). Regardless of Wang and De Neufville (2006), Cardin and De Neufville (2008), Mikaelian et al. (2011) and Cardin (2014) the other marked authors from manufacturing (in Tables 2 &3) have not made a distinction between flexibility types and enablers. Rather they have mentioned various samples of flexibility types and enablers implicitly.

It should be noted that manufacturing flexibility is often conceived of as hierarchical (Sethi and Sethi, 1990, Koste and Malhotra, 1999). The underlying assumption is that the flexibility of sub-components (e.g., technology; human resources; supply networks) contribute to overall system flexibility at 'higher-level' (Volberda, 1996, Koste and Malhotra, 1999). Ways of achieving flexibility are then classified based on the tier they belong to (Sánchez and Pérez, 2005). For example, Koste and Malhotra (1999) map the sources of flexibility for manufacturing into four tiers of 'individual resources', 'shop floor', 'plant', 'functional', and 'strategic business unit'. Since the flexibility hierarchy does not fit in the nature of multifunctional flood defences, the approach of manufacturing has not been taken into account in this paper.

It is argued that the proposed framework including four questions and eight characteristic features can be instrumental in structuring the discussion of flexibility in the context of multifunctional flood defences for two reasons. First, the fours questions of the framework represent the commonalities observed in the literature that are consistent across the flood management, real options, and manufacturing publications. Second, the terms applied for characterising flexibility have been sporadically applied in discussion about adaptation to climate change (Fankhauser et al., 1999, Smith et al., 2000, Adger et al., 2005). Hence, the terms are known and can also be used in the context of multifunctional flood defence development.

However, the framework is not claimed to be universal and comprehensive. It is aimed to be useful for different actors and stakeholders involved in decision making and development of multifunctional flood defences. The end goal is to improve the overall effectiveness of the project in accordance with their perspectives and interests. Thus, the following working definition of flexibility is proposed:

Flexibility is a multifunctional flood defence system attribute that enables responding to changing conditions, in order to reduce the negative consequences, and to exploit the positive upsides of uncertainty and change, in a performance-efficient, timely and cost-effective way.

4.4 The application

This section demonstrates the developed framework by applying it to the conceptual design of a multifunctional flood defence. The investment interventions required for the development of multifunctional flood defence are capital intensive and irreversible. Hence, the framework is intended for planning the structure, taking into account the dynamics in the environment and changing circumstances. The objective of the process is to support including flexibility in the design and management of multifunctional flood defence in such a way to not only meet today's requirements, but also to accommodate the future needs.

The illustrative case study of this section is anonymous. The context for the case study application is taken from an existing multifunctional flood defence in the Netherlands, in which a series of residential and commercial buildings have been built on top of a sea dike. However, the information about the development process of these structures is not available to the authors. The context can serve as an example of a situation in which various types of uncertainties and changes associated with the development of a multifunctional flood defence need to be addressed.

The sea dike of the case study represents a man-made, earthen structure that is in place to prevent the hinterland areas from high sea water levels and wave attacks. The dike is assumed to be a section of the whole flood defence system, which protects an urban area along the coast. The profile of the dike is considered to be the same all along the section. In the Netherlands, the strength and stability of the dike sections are checked periodically to maintain the required level of safety. Presumably, the latest visual inspection of the dike has demonstrated that the dike section under study does not comply with the current safety standards and has to be reinforced. The decision on the extent of the reinforcement, however, is faced with uncertainty about various influencing factors.

In this example, the reinforcement of the section implies increasing the width and height of the dike. The extra space required has also been planned for the development of a residential area. To deal with the conflict of reinforcement and urban development, it has been suggested to construct buildings on top of the dike with the same length as the dike. It is, however, very difficult to determine the size (the number of floors) of the high rise buildings because the demand for houses is not predictable, especially when they are integrated into a dike.

The dike and buildings are capital intensive and irreversible interventions. In anticipation of various uncertainties about the future developments, it has been realized that it is favourable and perhaps more cost-effective to incorporate flexibility in planning of the coupled structure of this example. In order to explicitly address the desire for 'flexibility', it is necessary to provide a common basis for discussing flexibility without ambiguity and confusion. To do so, the developed framework is used to structure the discussions with the aims of investigating the design considerations for the dike and buildings. The framework is represented as shown in Table 5. Q1 to Q4 are the four questions of the framework. Each column in Table 5 represents the associated characteristic features of flexibility for the relevant questions. The intention is to determine the characteristic features of flexibility that are as clear, unique and independent as possible. Completeness in not attempted, although each box should provide sufficient information for handling the problems faced.

Table 5, the framework in the form of a table to be filled for the case study

Q1		Q2		Q3		Q4	
Change	**Uncertainty**	**Goal**	**Capabilities**	**Temporal**	**Mode of response**	**Types**	**Enablers**
…	…	…	…	…	…	…	…

Within this case study, the framework is first applied for discussing flexibility for the dike and the buildings developments individually. Previous publications are used to derive the necessary information for each step of the framework. Afterwards, the options for flexible design of the two structures are combined, and the impacts of the coupling on their flexibility are further explored.

4.4.1 Flexibility for the dike

In this example, for the sake of illustration, only the sea level rise uncertainty is addressed. It is assumed that the global warming causes a gradual and long term changes in the sea water level. It is assumed that the dike is originally designed to the height equal to the highest recorded water level plus a pre-determined safety margin. However, uncertainty about the magnitude of the sea water level makes it difficult to determine the height of the reinforced dike. Moreover, the reinforcement decision has to be made in the face of scarce resources whilst the people and assets to be protected are not static, but evolve over time. Therefore, the goal of flexibility consideration in this example is to enable adaptation to the changing threat of flooding while maintaining the required level of safety. To do so, flexibility is intended to lessen the costs of dike reconfiguration in response to the sea water level changes. Changes in the water level are anticipated to occur gradually and over a long term though there is no agreement on the magnitude of change. Since the consequences of a considerable rise in the water levels on flood hazard would be substantial, an anticipatory response (proactive) is required to take action before reaching a threshold water level. A common strategic flexibility type, proposed in the literature, for coping with sea level rise is the option to delay the reinforcement interventions until uncertainties unfold over time. Two suggested possibilities for the postponement are, widening the dike now and allowing for future heightening of the dike (as shown in Figure, 6a) , and reserving the land around the dike for widening and heightening of the dike in the future (as shown in Figure, 6b) (Woodward et al. 2011). The dike can be proactively reinforced when the mean sea water level passes a pre-determined threshold value.

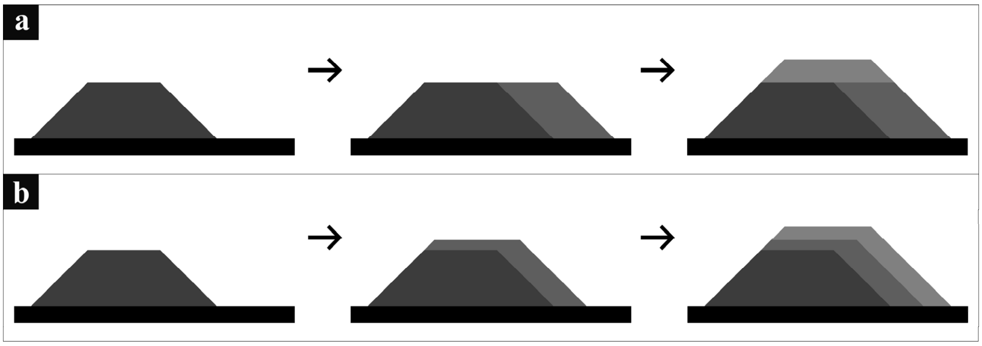

Figure 6, two possibilities for enabling the option to delay the dike reinforcement interventions.

Table 6, summarizes the characteristic features that have been discussed above.

Table 6, the determined characteristic features of flexibility for the dike design

Q1		Q2		Q3		Q4	
Change	**Uncertainty**	**Goal**	**Capabilities**	**Temporal**	**Mode of response**	**Types**	**Enablers**
The mean sea level rise	The extent of the mean sea level rise	To maintain sufficient safety	Reducing the costs of future adaptation	Change is gradual and long term	A proactive response is required	The option to delay the investment interventions	-Widening the dike base - Reserving the land around the dike

4.4.2 Flexibility for the buildings

The demand for living in high rise buildings is subject to change. There are various uncertain socio-economic factors that govern the demand. The uncertainty about the changes in demand selected to be addressed in this example. The goal of flexibility is, then, to accommodate the current demand for housing, and to enable profitability in case of higher demand in the future. The changes in the housing market are gradual. Therefore, handling the demand changes requires strategic planning for maintaining competitiveness and profitability. Generally speaking, gaining competitive advantage requires controlling the change after the occurrence in a reactive way (Golden & Powell 1999). Therefore, a reactive mode of response is intended here for addressing the changes in the demand for housing. A recommended option in the literature is the option to expand the investment on housing, which provides managerial flexibility to react to favourable demand changes. This option can be enabled by constructing the buildings on a stronger foundation with the possibility of a vertical expansion of the buildings in the future (De Neufville and Scholtes, 2011). As shown in Figure 7, the building can be expanded vertically, by adding floors, along with increasing demand. Table 7 summarizes the characteristic features of flexibility for the buildings.

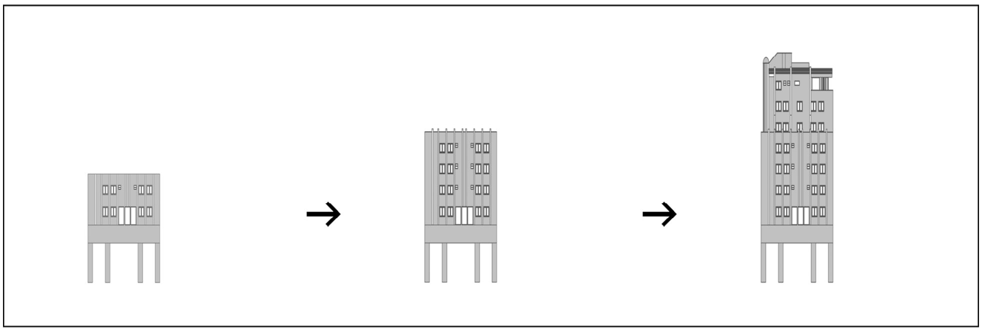

Figure 7, the possibility for enabling the option to expand the number of floors of the buildings

Table 7, the determined characteristic features of flexibility for the buildings

Q1		Q2		Q3		Q4	
Change	**Uncertainty**	**Goal**	**Capabilities**	**Temporal**	**Mode of response**	**Types**	**Enablers**
The demand for housing	The extent of the demand change	To accommodate the demand and maintain profitability	Reducing the costs of response	Change is gradual and discrete	A reactive response is required	The option to expand the investment interventions	Building on a stronger foundation

4.4.3 Superposition of flexibilities

In the preceding sub-sections, the design alternatives with embedded flexibility were determined for each structure individually. When the two structures are coupled, the superposition of the flexible alternatives is necessary. Among the various possibilities, two are considered here as shown in Figure 8. In the first possibility (a) the dike base is widened initially and the height of the dike is raised in phases. In the second (b), the area around the dike is reserved for reinforcement interventions, and both the height and width of the dike are extended according to the requirements at that time. Primarily, it is expected that the buildings are raised when there is an increase in the demand.

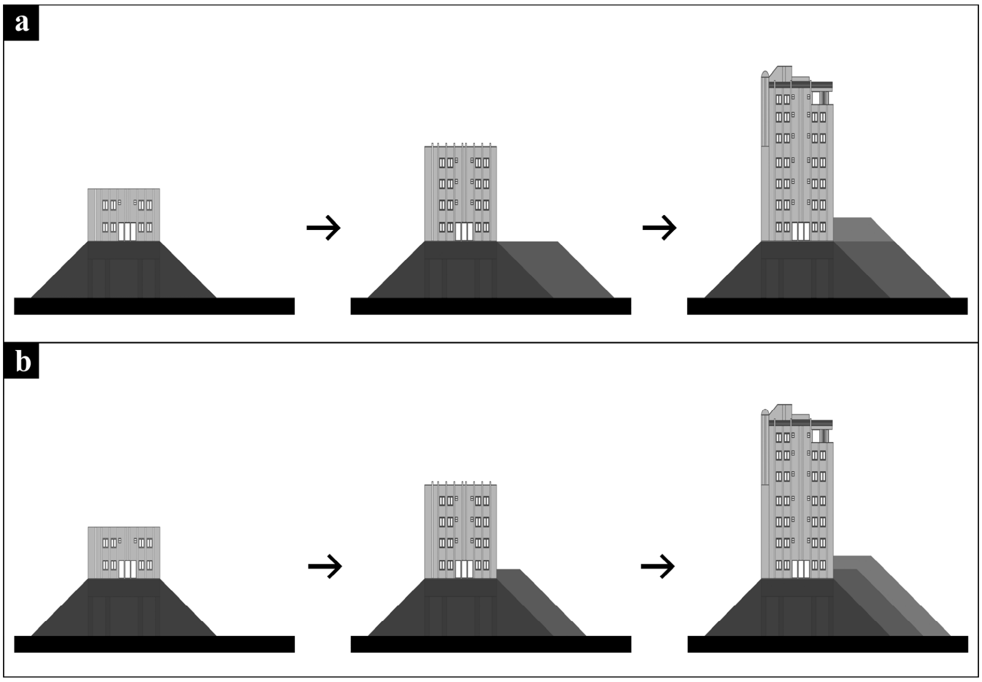

Figure 8, two possibilities for embedding flexibility in the design of a coupled structure

With the coupling of the two structures, some challenges and complexities emerge that impact the flexibility considerations. With the developed framework, the challenges created relevant to each characteristic feature are tractable. Some of the challenges relevant to each question of the framework are exemplified here.

Regarding the Q1, so far, the uncertainty and changes are treated separately for the two structures. However, the coupling of the two structures may lead to interference of changes in one structure with the performance of the other. For instance, at each period within which the buildings are raised, some additional weight is added on top of the dike. This extra weight may cause dike instability. As the demand is uncertain, the degree of impact will be uncertain, but important. Therefore, demand uncertainty has to be taken into account for the design of the dike as well as the design of the buildings itself.

Regarding the Q2, an interesting fact that can be inferred is that a high rise building adds some extra height to the dike. If the series of buildings on top of the dike are designed in such a way to not allow high water levels to pass through to the hinterland, the dike can be built lower. This in turn means that constructing the buildings with water retaining walls can contribute to delaying the reinforcement investments for a longer period of time, and, therefore, enhances the flexibility in reinforcement planning.

Regarding the Q3, the time span of change and mode of response are the factors that impact the frequency of adaptation sessions. Coupling may challenge these exercising times. For example, if the dike is raised then the ground floor of the buildings will be out of order. This may result in the need for adding to the number of floors, even if housing demand has not changed. This means that the exercise times for the buildings would be not only dependent on the demand changes, but also the changes in the sea water level.

Relating the Q4, as a result of the challenges discussed above, it can be inferred that the process of determining the flexibility types and enablers has to be recursive, and iterative. It should begin with identifying flexibility for the dike and buildings, determining the various ways in which the options for flexibility can be combined, assessing the feasibility of each option, and selecting among them.

4.5 Discussion

The framework of the paper was used to structure the discussion of flexibility in the conceptual design of a multifunctional flood defence. It can be seen that, use of the framework facilitates identification of potential flexibility attributes as well as handling the complexities created by coupling the two structures through an iterative process.

Furthermore, planning for coupling the dike and the buildings requires collaboration between the people engaged in the design and management of the dike, and the buildings. To prevent mutual misunderstanding, it is of utmost important to ensure that people with different backgrounds have the same understanding of the subject under discussion. The step-by-step application of framework for the case study demonstrates that is possible to structure flexibility discussion for the dike and building in the same way and without confusion.

Additionally, the characteristic features of flexibility can support the evaluation process as well as the identification process in two ways. First, the extent to which flexibility achieves its goal can be used for assessing the added value of flexibility as applied by some scholars such as Woodward et al. (2011) and Linquiti and Vonortas (2012). Second, the quantified capabilities of flexibility are often applied as indicators for measuring the degree of flexibility provided by a specific option. Those indicators can be used to compare and prioritize the developed options for flexibility (Gupta and Goyal, 1989).

Overall, it can be claimed that the four questions and eight characteristic features enhance the clarity about the concept of flexibility, and can serve as a first step for developers of multifunctional flood defence to formulate clear plans for identifying, evaluating and enhancing the critical flexibility required.

4.6 Summary and Conclusion

This paper was prompted by the observed ambiguity about the meaning and characterization of flexibility in the flood management literature. Subsequently, a framework was developed aimed at enhancing consistency and clarity in discussing, identifying and evaluating flexibility for the development planning of multifunctional flood defences. The framework consists of four questions and eight characteristic features of flexibility. The questions address the consistent commonalities found in the literature and are used to structure the discussion of flexibility. In order to clarify flexibility for multifunctional flood defence, the eight characteristic features of flexibility in association with the four questions were distilled from a selection of thirty-five publications from real options and manufacturing. However, many scholars have taken the identified characteristic features in their work implicitly or explicitly into account. The information presented in Tables 3 and 4, shows that the characteristic features altogether have not been comprehensively addressed before. The paper argues that the proposed framework including four questions and eight characteristic features can be instrumental in structuring the discussion of flexibility in the context of multifunctional flood defences.

Having developed the framework, the functionality and potential of the framework were explored for an illustrative case study. The case application showed that the framework can indeed be used for structuring the discussion of, and preventing confusion and fuzziness about the meaning of flexibility. This is of particular importance for multifunctional flood defence developers to have a common ground for communicating about flexibility since they come from different disciplines. Furthermore, the framework illustrated the relationship between the flexibility and design considerations for multifunctional flood defence. Additionally, areas that need more attention in the discussion about flexibility were outlined by the framework. It was concluded that the framework can be used by developers multifunctional flood defence as a step-by-step guideline to formulate clear plans for identifying, evaluating and enhancing the flexibility critical for multifunctional flood defence.

The study has raised several issues that should be further addressed in future research:

1. The impacts of multifunctionality on required flexibility for the flood defence deserves further clarification. Further research should address the interactions between the dike performance and its secondary functioning in relation to the required flexibility for multifunctional flood defence.

2. This study is the first step towards identifying and evaluating flexibility for multifunctional flood defences. Further research is required to develop an evaluation model for assessing the cost-effectiveness of flexibility considerations in developing multifunctional flood defences. Use of social cost-benefit analysis methods can be advantageous for a systematic and cohesive assessment of a broad range of impacts caused by flexible design and development of multifunctional flood defences.

3. However, the illustrative case study demonstrated the applicability of the proposed framework of the paper. There is a need for exploring the instrumentality of the framework for real cases. This can be done by conducting targeted interdisciplinary workshops and interviews. Also, it is interesting to test the applicability of the framework in other, non-Dutch, cases worldwide.

4. Further research is required to explore the literature in other areas than real option and manufacturing. Fields such as business development, complexity science, or urban development may potentially contribute to further revision and refinement of the framework and the distilled characteristic features.

5 An Application of the Functional Resonance Analysis Method (FRAM) to Risk Analysis of Multifunctional Flood Defences in the Netherlands[2]

"It is change, continuing change, inevitable change that is the dominant factor in society today. No sensible decision can be made any longer without taking into account not only the world as it is, but the world as it will be."

Isaac Asimov

"As our case is anew, so we must think anew, and act anew. We must disenthrall ourselves"

Lincoln to Congress in 1862

5.1 Introduction

Reinforcement and maintenance of flood defences has a high priority for the Dutch Government. Often, improving the flood defences requires additional space, which is scarce in the densely populated areas in the Netherlands. All the demand for housing, employment, transportation and farming has to fit in a relatively small surface area, where the safety and quality of the living environment and the landscape need to be maintained as well (Ligtvoet et al., 2009). Multifunctional use of flood defences is proposed as a promising solution for dealing with the conflicts of flood protection and urban development as well as enhancing the

[2] Chapter is based on: Anvarifar, F., Voorendt, M. Z., Zevenbergen, C., & Thissen, W. (2017). An application of the Functional Resonance Analysis Method (FRAM) to risk analysis of multifunctional flood defences in the Netherlands. Reliability Engineering & System Safety, 158, 130-141.

cost-effectiveness of reinforcement interventions (De Groot, 2006, Veerman and Stive, 2008, Stalenberg, 2010, Tettero, 2013, Van Loon-Steensma et al., 2014).

Similarly to other types of critical infrastructures, the operating environment of every multifunctional flood defence system is dynamic, evolving and unpredictable (Egan, 2007, Ajah, 2009, Petersen and Bloemen, 2015, Neumann et al., 2015). Sustaining the desired performances of multifunctional flood defences under both expected and unexpected conditions requires an intrinsic ability and flexibility to properly manage and cope with various changes and their consequences (Olsson et al., 2004, Comfort, 2005, Folke, 2006, Walker et al., 2013). Both the negative and positive impacts arising from these changes have to be taken into account to plan for not only minimising the unwanted negative outcomes, but also to take advantage of the opportunities for improving the system performances (Folke et al., 2005, Rogers and Louis, 2008, De Neufville and Scholtes, 2011, Hollnagel, 2011). Conducting such a risk analysis early during the conceptual design phase can help the designers to identify and handle the risks before they may occur.

Multifunctionality can induce dependencies between the system components, which leads to complexities in risk analysis of such a system (Woods and Branlat, 2010, Johansson and Hassel, 2010). Once the functions are combined, they become part of a broader socio-technical context in which the well-/mal-functioning of the system depends not only on its technical performance, but also on the role of humans as operators, inspectors, and users of the system (Comfort, 2005, Pahl-Wostl, 2007b). Indeed, there is a growing body of evidence, illustrating that human capabilities such as anticipation, sense-making and learning have a profound and crucial impact in intensifying and/or preventing the causes and consequences of disastrous flooding events (see for example, Gerritsen, 2005, Farber et al., 2006, Cigler, 2007). Effective risk analysis of multifunctional flood defences, thus, requires capturing the complexity of the relationships between the human actions, technical functions, and the environment of the system (Perrow, 1984, Berkhout, 2002, Leveson, 2011).

This research investigates the application of 'Functional Resonance Analysis Method (FRAM)' (Hollnagel, 2012) for qualitative risk analysis of multifunctional flood defences. The term risk is used in this research to denote the uncertain outcomes that could be either positive or negative. The objective is to identify how the dependencies caused by multifunctional use of flood defences can strengthen or weaken the desired performances of the system when there is a change in its external environment. FRAM is selected because it enables modelling both negative and positive events resulting from (intended and unintended) dependencies between the functional components of a multifunctional flood defence(Lundblad et al., 2008). The premise of the FRAM is based on the generic steps of the system analysis (Browning, 2001) to analyse the system functions by breaking apart the system into the functional components that are relatively known, outlining the dependencies between the components, and investigating the impacts of the dependencies on system performances. In doing so, the method is customised and applied to compare four alternative designs developed for constructing a multifunctional flood defence in a case study in the Netherlands. The results of the analysis are used to demonstrate the implications of the customised FRAM for risk assessment and management of multifunctional flood defences.

The rest of the paper is organised as follows. Section 2 provides the background information about the multifunctional flood defence system definition and dependencies and the methods of functional analysis which can be applied for the purpose of risk analysis. Section 3 briefly introduces the FRAM approach and the required changes to customise FRAM for the use in the context of multifunctional flood defences. Section 4 describes the case study and the four alternative designs of a multifunctional flood defence. Section 5 presents the application of the model in the case study and the result of the analysis. Finally, Section 6 summarizes the content of a paper and provides some suggestions for the future works.

5.2 Towards multifunctional flood defences

5.2.1 System definition

Traditionally, many flood defences in the Netherlands also serve other functions such as housing, transportation, recreation, etc. In the majority of cases, the only visible function is actually the secondary function of the flood defence (TAW, 1998). Fortifications and quays are two typical, historical examples of such multifunctional structures. Fortification acts as a defensive wall against hostile attacks, and quays are used for loading and unloading vessels. Both types of structures have also been used for protecting inland areas against high water levels (Stalenberg, 2010). More recently, the concept of multifunctional use of flood defences is receiving a renewed interest. However, there is no generally agreed definition of multifunctional flood defences presented in the academic literature and Dutch reports.

From a structural point of view, Van Veelen et al. (2015) argue that a multifunctional flood defence is a structure comprising of at least two objects. Where the core structure is a water retaining structure, there is a secondary object placed as part of the flood defence, which is not intended for flood protection. Ellen et al. (2011) merge the structural and functional standpoints and distinguish four possibilities for multifunctionality based on the amount of change in the original profile of the flood defence and the relative location of the secondary object. On the other hand, Van Loon-Steensma and Vellinga (2014) describe a multifunctional flood defence as a combination of functions such as transport, housing, agriculture, nature and recreation with the primary function of flood protection.

What can be inferred from real cases and the above-mentioned interpretations is that multifunctionality stands for a combination of one or more secondary function(s) with the primary function of flood protection, which is achieved by co-locating and connecting the associated structures. This resembles the definition of 'system' as presented by Bishop (2015). Additionally, multifunctional flood defence systems also represent the characteristics of socio-technical systems, as defined by Appelbaum (1997). In this paper, the working definition of multifunctional flood defence refers to:

A zone that is primarily used for flood protection, yet serves other non-water retaining functions (e.g. transportation, housing).

Principally, there is no limit on the number and type of functions that can be combined with the flood protection function. The combination of the function(s) is considered as multifunctional only if the structure of the secondary function (secondary object) locates partly or fully in one of the standard flood protection zones around the flood defences as defined by Dutch Law (TAW, 1998).

5.2.2 System dependencies

Multifunctionality does not only refer to a higher concentration of several activities in a smaller space, but also implies for inducing various types of relationships between the combined functions. If the created relationships are such that the state of one function of the system becomes reliant on- or influenced by the state of another one, then there is a dependency between them (Caporaso, 1978). This section sets the stage for addressing these dependencies and their impacts in the context of multifunctional flood defences. Since different interpretations of the term 'dependencies' exist in the literature; it is first needed to specify its meaning of the term in this research.

Rinaldi et al. (2001) argue that a unidirectional relationship between the states of two systems is called 'dependency' while 'interdependency' represents bidirectional relationships between them. McDaniels et al. (2007) use the term 'interdependency' to describe unidirectional relationships between the systems. Johansson and Hassel (2010) further explain that interdependencies refer to the relationships between two combined systems while dependencies represent the relationships within a system. In a slightly different way, Hollnagel (2013, 2012) uses the term 'dependency' to indicate the relationships between the functions of a system. Where the intended dependencies refer to pre-defined relationships between the functions, the unintended dependencies indicate the potential relationships that can be realised in particular situations. The Hollnagel's interpretation is adopted in the present paper to describe the intended and potential (unintended) relationships between the functions of a multifunctional flood defence system, either mutual or unidirectional.

Rinaldi et al. (2001) classify the intended relationships among the infrastructures components based on the mechanisms that connect them. Subsequently, Zimmerman (2009) selects and indicates the physical (or functional) and geographical relationships as the most relevant types of dependency to be considered for water related infrastructures. These two types can also reflect the intended relationships between the components of a multifunctional flood defence, which are caused by combining and relating the functions and/or co-locating and connecting the associated structures.

5.2.2.1 Physical dependency

Physical dependency refers to the situation in which the state of one function is intentionally designed to be dependent on the other function. In other words, physical dependency implies an intended link between the functions in such a way that the performance of one function becomes a requirement for the other function to perform its desired task (Rinaldi et al., 2001, Dudenhoeffer et al., 2006). Three recognizable levels of physical dependency for multifunctional flood defences in the Netherlands are:

1- The flood protection and secondary functions are fully independent. However, the secondary object (the structure associated with the secondary function) is placed in the flood protection zone. The two functions perform their intended tasks as if they were not co-located. For example, the housing function can be conducted independently from the flood protection.

2- The flood protection and secondary functions are fully dependent in such a way that one function cannot be completed before the other one is done. Navigation locks (gates) are among the common examples of hydraulic structures with dual functioning. A lock is a structure that is used for flood protection as well as navigation by regulating the water levels at either end. While the function of navigation requires the lock gate to be open, the function of flood protection requires the gate to be fully closed.

3- The flood protection and secondary functions are partly dependent. However, the functions can be conducted independently. One function is also intended to accommodate the other function of the system. An example of this situation has been operationalized in the 'Museumpark' in Rotterdam City in the Netherlands, where a parking garage is placed underground in such a way that it can also store the excess surface water during heavy rainfall. The parking structure contributes to flood prevention without any major interference with its primary function.

5.2.2.2 Geographical dependency

Geographical dependency occurs due to co-location of the structural elements of a system in such a way that a local environmental event can affect all of them (Rinaldi et al., 2001, Dudenhoeffer et al., 2006). Accordingly, the shared use of land for co-locating a secondary object in the flood protection zone of a flood defence results in a close spatial proximity between them. This intended geographical proximity relates the states of the two functions in such a way that one function may potentially impact the performance of the other function. For example, it is generally believed in the Netherlands that placing any structure in the flood protection zone affects the flood defence performance negatively.

The physical and geographical dependencies as defined in this section are intentional. This is because the decision for combining the functions is made by the developers of a multifunctional flood defence. It is, however, expected that the combination of the functions may create unwanted dependencies between their states that are not intended by the developers of the system. These are called potential dependencies because they can impact the desired performances of the system only during the occurrences of particular events (Hollnagel, 2012).

The present paper is concerned with these potential (unintended) dependencies. Herein, it is assumed that the physical and geographical dependencies are important factors that determine to what extent the performance of one function can impact the performance of the other function during an uncertain event that may happen in the future. It is expected that due to the possibility of change propagation and cascading failures, the consequences of dependencies on the overall system performances can be far more complex than a single disruption of one system component (Pederson et al., 2006, Nieuwenhuijs et al., 2008, Zimmerman, 2009, Merz et al., 2015). In order to be able to address the unexpected impacts during the process of risk management, the next section discusses the methods that can be used to assess the consequences of the intended dependencies between the functional components of a multifunctional flood defence.

5.2.3 Functional modelling methods for risk analysis

Reliability analysis techniques are perhaps the oldest methods developed for risk analysis of technical systems in the years following World War II (McIntyre, 2000, Leveson, 2003, Stoop, 2004) though the word 'reliability' was first coined by Samuel T. Coleridge in 1816 (as stated by Saleh and Marais (2006)). The flood defences in the Netherlands are also designed and assessed based on the risk-based methods in which a flood defence is modelled and assessed via the use of reliability analysis methods (Voortman, 2003, Van Gelder et al., 2009, Buijs et al., 2009). Reliability is a value indicating the probability of failure-free performance of a flood defence over a specified timeframe and under specified environmental conditions (Buijs et al., 2007). The premise of reliability analysis is that the nature of the system behaviour is stochastic and can be explained by decomposing the system into independent components (Bier et al., 1999, Pollack, 2007, Rouse and Serban, 2011, Mai et al., 2008). However, the reliability analysis methods can be applied for the design of multifunctional flood defences (Van Mechelen, 2013). It is argued in the literature that the reliability analysis, is inadequate to address the risks associated with the complex relationships between the components of socio-technical systems (Rasmussen, 1997, Baxter and Sommerville, 2011) for several reasons.

The first of these reasons follows from the way that the various methods of reliability analysis such as effect analysis (FMEA), fault tree analysis (FTA), and event tree analysis (ETA) treat component failure and/or human error (Leveson, 2004, Peyras et al., 2006). The system components are analysed in separation, since if combinations of failures are considered, the task would become intractable (White, 1995, Öhman, 1999, Ruijters and Stoelinga, 2015). Second, reliability methods define success as a lack of component failure (Buijs et al., 2007, Wang et al., 2015), while the well performing of socio-technical systems is an emergent property of the whole system (Leveson, 2003, Merz et al., 2015). In fact, a combination of correct and incorrect behaviours may cause malfunctioning and a greater probability of failure does not necessarily result in a greater risk (Dawson et al., 2005, Bleda and del Río, 2013). Last but not least, reliability analysis methods are explicitly aimed to predict and eliminate the root causes of some major failures (Di Pasquale et al., 2013). The static nature of these methods makes them incapable of addressing the unpredictable and dynamic performance of socio-technical systems (Leveson, 2003, Qureshi, 2007, Hollnagel, 2014b). Consequently, the aim is to control the system performance, while ignoring the fact that the system performance cannot be fully controlled as much as it can be influenced and adjusted (Leveson, 2011, Hollnagel, 2012, Rouse and Bodner, 2013).

Complementary to reliability analysis methods, functional modelling is an established way of analysing the risks associated with the complexity of the dependencies within the socio-technical systems (Gharajedaghi, 2011, Woltjer, 2009, Teilans et al., 2011, Tangsuksant and Prompoon, 2007). Functional modelling approaches treat the system as a whole and focus on functional abstraction rather than structural decomposition (Rasmussen, 1997, De la Mata and Rodrıguez, 2007), and therefore enable elaborating the system from multiple perspectives (Piatyszek and Karagiannis, 2012, Greenwood, 2012, Alvarenga et al., 2014). In other words, such models are capable of representing and analysing the relationships that hold or emerge among human actions, structural components, and the environment and the impacts created by the combination of all three (Turner et al., 2003, Farber et al., 2006, Baxter and Sommerville, 2011, Dalpiaz et al., 2013, Hollnagel, 2015). Among the various methods developed for functional modelling, the present paper describes and compares the two systematic methods of structured analysis and functional resonance analysis (Review of all the methods can be seen in Woltjer et al., 2009, Alvarenga et al., 2014).

The ‘Structured Analysis and Design Technique (SADT)’ is a well-defined functional language (Ross, 1985) that has been standardized into the modelling language IDEF0 (Colquhoun et al., 1993, PUBs, 1993). IDEF0 applies the concept of parent-child diagrams to decompose a system into more fundamental components and focuses on action sequences However, the use of IDEF0 has been reported as a useful way of representing the social aspects of technical systems such as early warning systems for water treatment plants (Imran et al., 2010, Bevilacqua et al., 2014) and flood and landslide risk management (Bevilacqua et al., 2014) and the design of storm surge barriers (Willems and Webbers, 2003). IDEF0 suffers from a number of drawbacks that affect its suitability for risk analysis of multifunctional flood defences as socio-technical systems. First, the method treats human actions as mechanisms of conveying inputs to outputs. Therefore, human interests, preferences and politics cannot be taken into account (Greenwood, 2012). Second, the method provides a static representation of the system, indicating linear functional relationships. Hence, it cannot model the dynamics of the system behaviour, unless it becomes updated after the occurrence of each change (Kim and Jang, 2002, Woltjer, 2009, Greenwood, 2012). Additionally, IDEF0 is more focused on the description of the tasks and their orders than the means by which the tasks are performed. Knowing the details of the tasks is not sufficient to assess the risk related to the system performance variability and the shared aspects of different functions (Ang and Gay, 1993, Girard et al., 2016). Moreover, the IDEF notation is difficult for non-domain experts to understand and , in particular, to communicate it across various domains (Imran et al., 2010).

Within the resilience engineering community, Hollnagel and Goteman (2004) have further developed a functional modelling approach for retrospective safety analysis of socio-technical systems, which is called ‘Functional Resonance Analysis Method (FRAM)’. FRAM describes socio-technical systems by the functions they perform, rather than how they are structured (Woltjer, 2009). However, FRAM and IDEF0 are similar in terms of decomposing the system functions by using the four aspects of input, output, control, and resources. FRAM extends the number of aspects to include pre-conditions and an explicit notion of temporal constraints. The premise of the method is that the malfunctioning of socio-technical systems is an emergent phenomenon that can be better understood as a result of an alignment of (expected and unexpected) conditions and occurrences than as a pure consequence of technical failures and human errors (Hollnagel, 2012). FRAM has predominately been applied as a qualitative tool for retrospective accident investigation in areas such as aviation

(Nouvel et al., 2007, Woltjer and Hollnagel, 2007, Hollnagel et al., 2008, De Carvalho, 2011), and fire fighting (Åhman, 2013). The use of the method for prospective risk analysis is still under development and has limitedly been reported by Lundblad et al. (2008) for nuclear fuel transportation, Woltjer and Hollnagel (2008) for air traffic management, Sundström and Hollnagel (2008) for financial services systems and Rosa et al. (2015) for occupational risk analysis. More recently, it has been claimed by Hollnagel (2014a) that the FRAM method can also be used for risk analysis of construction work.

5.3 Methodology

The effectiveness of flood defences in reducing the risk of flooding is well-known though ensuring their desired performance faces significant challenges (Wilby and Keenan, 2012, Kind et al., 2014). On the one hand, the present methods are not able to fully describe and predict the performance of a single flood defence under controlled conditions (Buijs et al., 2007). On the other hand, the operating environment of flood defences changes constantly and is associated with uncertainties (Hall and Solomatine, 2008). Combining other functions with the primary function of flood protection further complicates the matter. The intended physical and geographical dependencies add new relationships between the system components and their operating environment, which can cause unintended dependencies that may strengthen or weaken the desired performances of a multifunctional flood defence. Identifying these potential dependencies during the early development phase of multifunctional flood defences can help improving the system design to handle the unexpected situations (Tangsuksant and Prompoon, 2007).

The examines the use of the FRAM (Hollnagel and Goteman, 2004, Hollnagel, 2012) for the qualitative risk analysis of multifunctional flood defences. It is acknowledge that there are many different methods developed for analysing the performance of socio-technical systems. For example, the cognitive models such as the Fuzzy Cognitive Maps (FCM) are aimed for representing the represent the casual relationships between the system characteristics such as events, actions, goals, values, trends (Stylios and Groumpos, 2002) for modelling political decisions (Szwed et al., 2014). The focus on modelling the decisions makes such methods incapable of representing the functions of a system with both technical and human components. FRAM is selected because it is a well suited method for representing the complex relationships between the functional components of socio-technical systems (Clay-

Williams et al., 2015). This method is used to outline the potential dependencies between the functional component of a multifunctional flood defence in order to provide input for the risk analysis (Woltjer and Hollnagel, 2008, Frost and Mo, 2014) with focus on demonstrating both the threatening and opportunistic situations (Hollnagel, 2012, Lundblad et al., 2008).

5.3.1 The 'Functional Resonance Analysis Method'

FRAM uses a novel representation of the system performance based on the concept of functional resonance that originates from wave theory in physics. The term 'stochastic resonance' is transferred to describe the variability of performance of the functions within a socio-technical system (Alvarenga et al., 2014). It is claimed that the inevitable changes in a system and its environment (physical, technical, political and institutional) can lead to variability in the performance of individual functions. Propagation and aggregation of the performance variability caused by the dependencies between the functions may result in unintended outcomes (Hollnagel and Goteman, 2004). The functional model of the system is developed and used to identify the potential dependencies between the functions for specific (retrospective or prospective) scenarios (Hollnagel, 2013). Extensive description of the FRAM can be found in Hollnagel and Goteman (2004), Hollnagel (2012), Hollnagel (2013). In short, FRAM is implemented in four steps as follows:

Step 1: Identifying and describing the functions

The basis for the risk analysis in the FRAM is the decomposition of the system into the functional entities that are involved in its everyday work to succeed. The functions refer to technical, operational, and organisational activities describing the normal day-to-day working of the system. The functions are characterised via six aspects of Input (I), Output (O), Precondition (P), Resource (R), Time (T), and Control (C) and are visualised as shown in Figure 9a. The six functional aspects are linked together to address the dependencies between the human-technical activities during the specified scenarios as sampled in Figure 9b.

Step 2: Characterizing the performance variability

This step of the risk analysis specifies the desired performances of the system and defines the qualitative indicators of performance variability for the target functions.

Step 3: Aggregating of performance variability

This step focuses on identifying the potential dependencies which propagate the performance variability based on the description of a particular scenario. This aggregation is also called functional resonance which denotes the name of the method (Hollnagel, 2012). Any detected possible functional resonance, for the specified event (or scenario), is taken as a discernible 'signal' of a threatening risk or an opportunity.

Step 4: Responding to performance variability

The developed functional model of the preceding steps is used to establish proper strategies (elimination, prevention, protection and facilitation) to cope with the possible occurrences of uncontrolled performance variability.

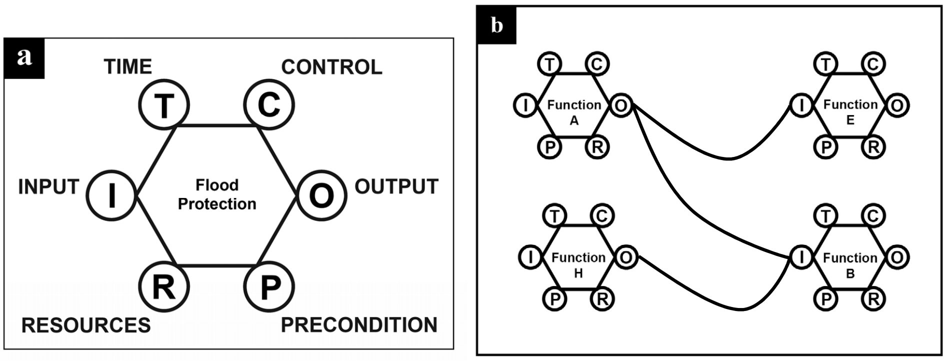

Figure 9, (a) the graphical representation of the six functional aspects; (b) a demonstration of the functional dependencies (modified from Hollnagel (2012))

Thus far, FRAM has been predominantly applied to retrospective safety and accident investigations, where the primary focus is on variability of human-centred functions. As stated by Hollnagel (2014a) the use of the method for risk analysis requires context-based adjustments in accordance with the needs of the analysis.

5.3.2 The customised method

This section proposes a customised FRAM approach to be applied for the risk analysis of multifunctional flood defences. The objective of the risk analysis process in this research is to support identifying the options for increasing the flexibility of the design alternatives and to provide additional criteria for prioritising the design alternatives. A multifunctional flood defence comprises of both human and technical functions, where the performance of the technical functions is not expected to vary as much as the human functions. Hence, FRAM needs to be customised for the purpose of this research.

FRAM is originally developed for identifying how the performance variability of a functional component can be propagated within the system to devise suitable strategies to handle the occurrence of variability. It is however, difficult to address the variability in the performance of the technical functions. Therefore, the customised FRAM is focused on delineating whether the impacts of variability in the human activities, as a result of an external change in the system environment, can have positive or negative impacts on a target function. Rather than handling the occurrences of performance variability of the influencing functional components, the end goal is to enhance the coping capacity of the target function which may be impacted in unexpected ways. The proposed steps of the analysis and the differences between the proposed method and FRAM are as follows.

Step 1: Describing the core functions

FRAM is developed for retrospective analysis of one specified system with certain functional components. The customised FRAM is used for prospective use analysis of several alternative designs for the obtaining a multifunctional flood defence. However, the primary function of the system is flood protection. Each alternative design may incorporate different types of secondary functions. This step is aimed for determining the core functions associated with each alternative designs. It is expected that the degree to which the secondary functions can impact the target function of the analysis will also depend on the intended levels of physical and geographical dependencies between the core functions of the system. Hence, it is also required to specify the level of intended dependency to be able to explore the influence of these intended dependencies on creation of potential dependencies and their impacts.

Step 2: Generating the scenario

FRAM is originally used to investigate the functional dependencies after occurrence of a specific event in a retrospective way. In order to use it in a prospective way, this step is added to generate a scenario of a future event and to explain how this prospective event may occur and evolve. The scenario may represent one or more changes relevant to the flood protection function, the secondary function or a combination of both. Additionally, the scenario specifications are also used to determine which functional components that should be included in the risk analysis process. Since some sub-functions may have similar names, in the visualized scheme, grey solid lines are used (e.g. in Figure 14) to connect the sub-functions to their relevant core functions.

Step 3: Characterising the performance variability

In order to be able to explore the impacts of the potential dependencies on a target function, it is necessary to develop the performance indicators. Any anticipated sign of improvement/deterioration in the performance of the target function is used as an indicator of performance variability. The meaning of variability in the outcome of a function may not be the same for the developers of flood protection and secondary functions. This step is to clarify the meaning of variability in the outcome of the target function(s). It is possible to use the terminology of FRAM for describing variability type (time, precision) or, to develop other criteria that fit the context of a specific case.

Step 4: Identifying the potential impacts

The use of FRAM in retrospective accident investigations enables the occurred variability to be detected. For a prospective risk analysis, it is hardly possible to take into account all the imaginable types and aggregations of variability for an event that has not yet happened. For instance, while it is feasible to investigate the impact of human action on the flood protection function, it is neither practicable nor necessary to specify the degree of variability in that action. Instead, it is more pragmatic to investigate whether the performance of the target function can become potentially influenced positively or negatively during a specified scenario. Hence, this step explores whether the involved sub-functions in a specified scenario can likely improve or deteriorate the performance of the target function. The positive (improving) and negative (deteriorating) impacts are visualised by the use of different types of lines (preferably coloured lines) connecting the impacting and influenced functional aspects. The target function is shown by a bold hexagon.

Step 5: Synthesizing and applying the results

Risk analysis can be conducted at any stage of the lifecycle of the system. This last step is focused on applying the results of the previous steps during the conceptual design phase. The identified positive and negative impacts are expected to be used in several ways. First of all, the identified impacts indicate the potential threats and opportunities that need more attention in each design alternative. Second, the results can also be used to compare and assess the intrinsic coping capacity of each alternative design in order to find the possibilities for increasing its design flexibility. Third, the number and type (positive/negative) of identified impacts provide extra criteria for determining better performing design alternatives during the conceptual design phase of multifunctional flood defences.

The last step of FRAM focuses on finding proper strategies to cope with the occurrence of variability. However, this research discusses the implication of the customized FRAM for increasing the flexibility of the design alternatives. Detailed analysis of the options for flexibility is out of the scope of the present paper, the following sections demonstrate the potentials of the customised FRAM for the risk analysis of a multifunctional flood defence.

5.4 Case study

The case examples are taken from two design alternatives developed for a multifunctional flood defence in Katwijk, the Netherlands. Examples are developed in such a way to represent different levels of intended physical and geographical dependency. The functional model of each example is developed and used to explore the impacts of the secondary functions of the system on the flood protection function, as the target function. The identified impacts are then used to demonstrate the implications of the method.

5.4.1 Case description

Katwijk is a small coastal town located at the old mouth of the River Rhine, as shown in Figure 10. The last safety inspection of the area demonstrated the need for the construction of a new sea dike. It is planned to protect some 4000 people living in the city centre. The coastline near the town is a touristic area that lacks sufficient car parking space. In order to make a better use of space, the coastal authorities decided to make use of the area for flood protection as well as parking.

Figure 10, the location of Katwijk in the Netherlands (Source: Modified from Google Maps)

Two multifunctional flood defence schemes were initially proposed. The first plan was to construct a parking garage along with a new dike (Figure 11a). Herein, the 'dike' refers to a man-made soil body (an earthen structure) that is designed to resist high water levels and wave attack during extreme events (TAW, 1998). Both parking and flood defence are covered by sand. Therefore, this alternative is called 'dike in dune'. The context of this design represents the first alternative of the case study. The second plan was to construct a parking garage on the land side and a restaurant on the water side of a flood wall (Figure 11b). This combination of the three functions in a close spatial proximity is taken as the second alternative of the case study. The contexts of these two plans are used in this research for generating two pairs of alternative designs. Each pair demonstrates a different level of physical and geographical dependencies. Contrasting the two examples of each pair enables investigating the impacts of different levels of intended dependencies on flood protection function.

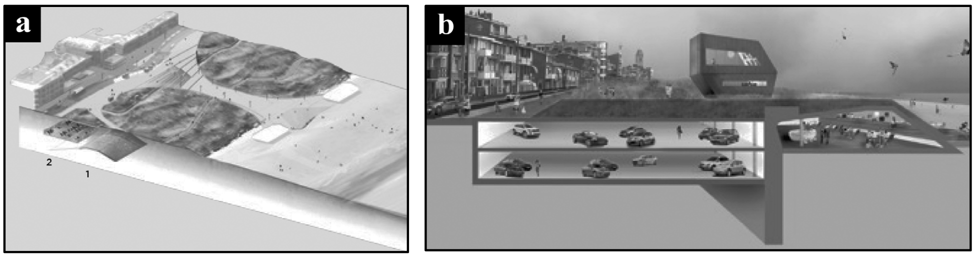

Figure 11, a) the first plan including a co-located see dike (No. 1) and parking garage(No. 2) (adopted from Oerlemans and Baldwin (2013)) b) the second plan comprising of co-located parking garage, flood wall and restaurant (adopted from Van Alphen (2015))

5.4.1.1 Description of Alternatives A1 and A2

The first plan including a sea dike and a parking garage is used to develop the Alternatives A1 and A2. These two alternatives are aimed at investigating how the different levels of geographical dependency can impact the performance of the flood protection function. Therefore, both alternatives include the same core functions, but with different levels of intended geographical dependency.

In both alternatives, a parking garage is built on the land side of the dike. The core function of the parking structure is 'providing car parks (F_{PP})'. It is not intended to contribute to the 'flood protection (F_{FP})' function. The first alternative (A1) represents the current situation in which the parking is built in the protection zone of the dike, where there is a short distance between the dike body and the parking structure. The second alternative (A2) shows the situation in which the parking is built next to the dike in such a way that there is no free space between the dike and parking. In both examples, the parking garage and the dike are covered by sand. Therefore, the parking garage and the dike will not be visible from outside. Figure 12, shows the cross sections of the two alternatives A1 and A2.

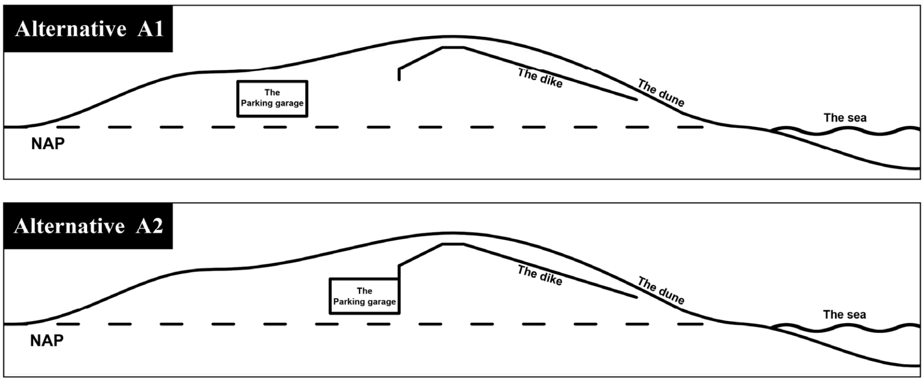

Figure 12, the cross sections of Alternatives A1 and A2, in which the parking garage is located in the land side of the dike

5.4.1.2 Description of Alternatives B1 and B2

These two alternatives are inspired by the second plan in which the multifunctional flood defence comprises of a parking garage, flood wall and a restaurant. Hence, the three core functions of the system are ‘flood protection’, ‘providing car parks’ and ‘food service’. Both Alternatives B1 and B2 include all the three functions, though the degree of physical dependency between the structures varies. The alternatives are aimed at investigating how the contribution of the secondary function in flood protection may impact the performance of the flood protection function.

In both alternatives, a restaurant is built on the water side and a parking garage on the land side of the flood defence. The flood defence of Alternatives B1 and B2 is not a dike, but a flood wall (a concrete structure). Alternative B1 demonstrates a case in which the parking garage and the restaurant have no intended contribution to the flood protection. The structures of the parking garage and restaurant are co-located but loosely connected to the flood wall. This means that the structures do not receive any structural support from each other. The restaurant is not flood proof and is expected to be washed away during an extreme event of 1/10000. In contrast, Alternative B2 shows three tightly connected structures. In this case, the restaurant and parking garage share a wall with the flood defence. The parking garage supports the flood wall against rotation. The restaurant is intended to resist high water levels and has to be fully closed during the extreme events. Figure 13, shows the cross sections of the two Alternatives B1 and B2.

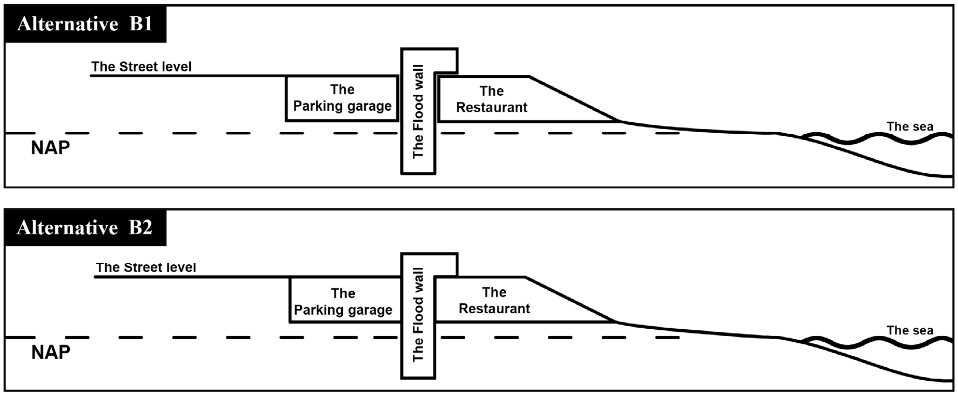

Figure 13, the cross sections of Alternatives B1 and B2, in which the parking garage is located on the land side of the flood wall and the restaurant is placed on the water side. The difference between the two alternatives is in the way the parking garage and restaurant are attached to the flood wall

5.5 The functional model of the alternative designs

The application of the proposed methodology is illustrated in this section. Ideally, the risk analysis should be carried out rigorously and comprehensively. Such an analysis requires a team of experts related to each function to bring together their field-specific knowledge and experience. The functional model and risk analysis of this section is solely focused on the impacts of the secondary function on the flood protection function. It is, however, acknowledged that the analysis can be extended to consider the impact of the flood protection function on the secondary function, too. The analysis is conducted via informal interviews with experts in flood defence design. Thus, the analysis is more illustrative than precise.

5.5.1 The core functions

The target function of the analysis in every alternative is ‘flood protection (F_{FP})’. In Alternatives A1 and A2 the two functions of ‘flood protection (F_{FP})’ and ‘providing car parks (F_{PP})’ are the core functions of the system. However, well performance of the flood protection function requires carrying out the sub-functions of ‘inspection (F_I)’ and ‘maintenance (F_M)’. Respectively, the function of ‘providing car parks’ requires the sub-functions of ‘inspection (F_I)’, ‘maintenance (F_M)’, and ‘operations (F_O)’. The ‘inspection’ and ‘maintenance’ sub-functions are organisational functions. For both core functions of F_{FP} and F_{PP}, the structural integrity of the buildings (the aspect of precondition) is the output of ‘maintenance (F_M)’ sub-function. Furthermore, the regular observation and monitoring of the two structures (the aspect of control) is the output of ‘inspection (F_I)’ sub-function. The sub-function of ‘operations’ refers to the human operations required for providing the parking service during normal working hours.

A description of the two core functions and their relationships with the sub-functions are provided in Table 8. Detailed explanations of the sub-functions are not necessary for the analysis of this section. It should be noted that for the flood protection function, the functional output is to provide safety by retaining high water levels. However, safety is part of the overall objective as well as a precondition. Safety as a precondition denotes the essential and required ‘structural integrity’ of every construction work in general. Furthermore, every flood defence is designed to resist high water levels for a specific period of time. This is considered as the time aspect of the flood protection function in this paper.

Table 8, the six aspects of the core functions of ‘flood protection’ and ‘providing car parks’ for the Alternatives A1 and A2

		Core functions	
		Flood protection (F_{FP})	Providing car parks (F_{PP})
Functional aspects	Input	High water levels	Demand for car parks
	Output	Safety via water retaining	Serviceability
	Precondition	Structural integrity (The output of ‘maintenance’ sub-function)	Structural integrity (The output of ‘maintenance’ sub-function)
	Resource	Flood defence structure (the dike and dune)	Parking garage structure Human operators (the output of human ‘operations’ sub-function)
	Time	Duration of the extreme event	Intended working hours
	Control	Safety assessment and monitoring (The output of ‘inspection’ sub-function)	Safety assessment and monitoring (The output of ‘inspection’ sub-function)

In Alternatives B1 and B2, in addition to the ‘flood protection (F_{FP})’ function, the other core functions of the system are ‘providing car parks (F_{PP})’ and ‘food service (F_{FS})’ at the restaurant. Similarly to Alternatives A1 and A2, each core function requires the sub-functions of 'inspection (F_I)' 'maintenance (F_M)', and 'operation (F_O)' for its day-to-day well-performance. In Alternative B1, the 'providing car parks' and 'food service' functions are not intended to cooperate in flood protection. In Alternative B2, the parking garage supports the flood wall against the failure mechanism of rotation. Therefore, the structural integrity of the parking garage (the output of the maintenance sub-function) becomes a pre-condition for the well-performance of the flood protection function. Table 9 summarises the six aspects of the three core functions. For the sub-functions, presented in parentheses, only the aspects that connect them to the core functions are explained.

Table 9, the six aspects of 'flood protection' function and 'providing car parks' and 'food service's functions for the Alternatives B1 and B2

		Core functions		
		Flood protection (F_{FP})	Providing car parks (F_{PP})	Food service (F_{FS})
Functional aspects	Input	High water levels	Demand for car parks	Demand for food
	Output	Safety via water retaining	Serviceability	Serviceability
	Precondition	Structural integrity (The output of 'maintenance' sub-function)	Structural integrity (The output of 'maintenance' sub-function)	Structural integrity (The output of 'maintenance' sub-function)
	Resource	Flood defence structure (the dike and dune)	Parking garage structure Human operators (the output of human 'operations' sub-function)	Restaurant structure Human operators (the output of human 'operation' sub-function)
	Time	Duration of the extreme event	Intended working hours	Intended working hours
	Control	Safety assessment and monitoring (The output of 'inspection' sub-function)	Safety assessment and monitoring (The output of 'inspection' sub-function)	Safety assessment and monitoring (The output of 'inspection' sub-function)

5.5.2 The scenario specifications and designated sub-functions

A thorough performance analysis of multifunctional flood defences may require consideration of various scenarios. Indeed, the potential dependencies and their impacts on flood protection function vary when the scenario specifications change. Such an analysis is, however, time consuming and requires a team of experts. Due to resource limitations, only one illustrative scenario of an extreme event is developed and applied in this section. The specified scenario should represent the entire pathway of the event during which the potential dependencies are realised. These dependencies are assumed to be 'fixed' during the occurrence of the scenario event (Hollnagel, 2012).

One advantage of the FRAM approach is argued to be the ability to investigate the impacts of simultaneously occurring events (Hollnagel, 2012). Even if one event is not expected to cause a significant change in the level of flood protection, the combination of the events may influence the actual level of safety provided by the flood defence to differ significantly from the desired standards. The scenario of this section addresses a disturbing event caused by a natural environmental change and by human actions. Accordingly, a relevant sub-function is added to the analysis.

A prolonged storm surge event is considered as an external change that can impact the performance of the flood protection function. Climate change is expected to result in rising sea levels and increasing storm intensities and wave attacks (KNMI, 2012). However, there is deep uncertainty about the magnitude, speed, and impacts of climate change (Rahman et al., 2008). There is abundant literature discussing the relationships between climate change impacts and the reliability of flood defences (Voortman, 2003, De Winter et al., 2012). Similarly, this section uses a scenario of a prolonged storm surge to analyse the performance of the flood defence under study. It is statistically expected that a storm with the return period of 10000 years lasts about 35 hours (HR-2006, 2007). Here, it is assumed that the storm surge has continued for a longer period of time. As a result, the sand cover (the dune) is washed away for Alternatives A1 and A2. Therefore, it is only the sea dike that must resist the high water levels and wave attack. To compensate for the safety provided by the layer of sand in the dune of Alternatives A1 and A2, the flood wall of Alternatives B1 and B2 is higher than the sea dike of Alternatives A1 and A2. Hence, no overtopping is expected to occur for the flood wall during the storm surge. For Alternative B1, the structure of the restaurant is washed away during the first day of the storm while it is strong enough to resist the storm in Alternative B2.

Another source of change that is addressed in this section is the human actions which represent an internal variability in the system. It is generally believed in the Netherlands that combining the flood protection function with other functions will negatively impact the level of safety provided by the flood defence. In order to explore this issue, it is assumed that a car crash has occurred in the parking garage resulting in a serious cracking. The crash has happened just before the storm starts. Therefore, there has been no time to repair the parking garage beforehand. Furthermore, in Alternatives B1 and B2, it is also assumed that the personnel of the restaurant have failed to close the windows and doors tightly. Although these human errors may cause failures, the adjustments and decisions during the emergency situation may also save a malfunctioning system (Hollnagel, 2012). To explore this, it is assumed that there is an emergency inspection of the parking garage after the car crash and during the storm. To address the car crash, the sub-function of 'parking the car (F_{PC})' is added to the functional model of the system.

5.5.3 Characterising performance variability and impacts

The performance of the flood protection function is determined and expressed based on the level of safety provided by the flood defence structure. In the Netherlands, every flood defence is designed to withstand water levels below a design water level. A flood defence is assumed to satisfy the desired level of safety if it is sufficiently high and resistant (Jonkman et al., 2008). Accordingly, variability in performance of flood protection can be characterised by a change in the type and likelihood of failure mechanisms that may happen. The failure mechanisms of concern for the present paper are derived from Kortenhaus et al. (2002), CIRIA (2013), Mai Van (2010), and Schweckendiek (2014). Subsequently, an impact on the outcome of the flood protection function refers to increasing or decreasing the likelihood of the considered failure mechanisms.

5.5.4 The identified impacts

For each of the four alternatives, graphical representations of the functions are used in order to show the identified potential dependencies and their impacts. The dependencies and their impacts are potential because they may possibly happen if the scenario unfolds in the future. Recognizing these impacts now, however, helps to improve the system flexibility in order to proactively cope with the anticipated events. In the visualised scheme, the grey lines relate the sub-functions to the associated core function. The positive impacts are shown by dash-lines and the negative impacts are depicted by dash-dot- lines.

5.5.5 Results for Alternatives A1 & A2

In Alternative A1, the car crash does not impact the flood protection function. It is, however, expected that the presence of the well-maintained parking garage will increase the chance of erosion at the interface of garage and the ground. Therefore, there is a potential dependency between the structural integrity of the garage (the output aspect of 'maintenance' sub-function) and the structural integrity of the dike (the precondition aspect of flood protection function) with a negative impact on flood protection function, as shown in Figure 14a.

In Alternative A1, the car crash can be a threat to the structural integrity of the dike and has a negative impact on the flood protection function. On the other hand, it is now expected that the parking garage protects the dike against erosion on its land side. Thus, a well-maintained parking has a positive impact on the structural integrity of the dike. Moreover, the emergency inspection of the garage during the storm may increase the chance of detecting a dike failure and, thus, has a positive impact on the flood protection function. The identified potential dependencies and their impacts are depicted in Figure 14b.

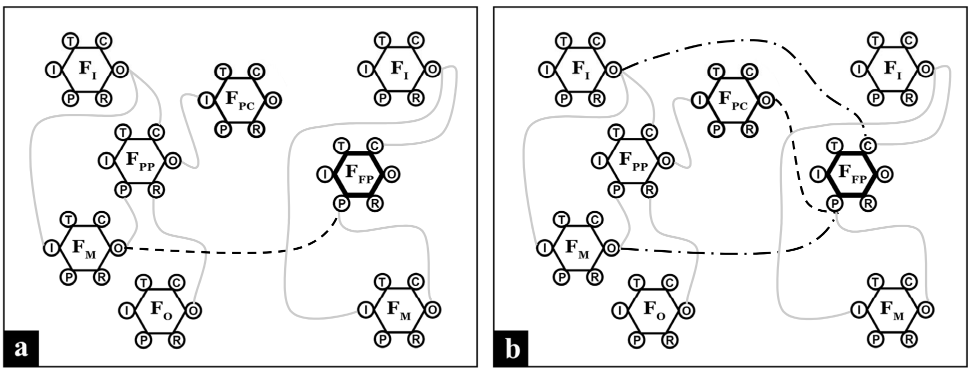

Figure 14, the identified negative (dash line) and positive (dash-dot line) impacts for Alternative A1 (a) and Alternative A2 (b). They grey lines connect the sub-functions to the associated core function.

5.5.6 Results for Alternatives B1 & B2

In Alternative B1, the presence of the parking garage and the car crash do not impact the flood protection function. On the other hand, the restaurant structure is washed away during the storm. Hence, a weakness in the structural integrity of the restaurant can increase the chance of erosion of the flood wall (negative impact). Moreover, failure in closing the windows and doors of the restaurant can accelerate the process of erosion of the flood wall. Hence, both of these potential dependencies impact the flood protection function negatively. The emergency inspection of the restaurant may improve the chance of detecting the flood wall's failure and impacts the flood protection function positively. Figure 15a, shows the identified potential dependencies and their impacts on flood protection function.

Alternative B2 shows several types of dependencies. Herein, the structural integrity of the garage is an essential precondition for the flood protection function. On the other hand, the car crash can increase the chance of the flood wall's failure and has a negative impact on the flood protection function. The emergency inspection of the garage can positively increase the chance of detecting a failure of the flood wall. The restaurant is a flood-proof building. Therefore, the structural integrity of the restaurant building during the storm has a positive impact on reducing the chance of flood wall failure. However, the failure in closing the doors and windows may diminish this positive impact. The emergency inspection of the restaurant can have a positive impact on detecting the flood wall's failure. The identified dependencies and their positive and negative impacts for this alternative are shown in Figure 15b.

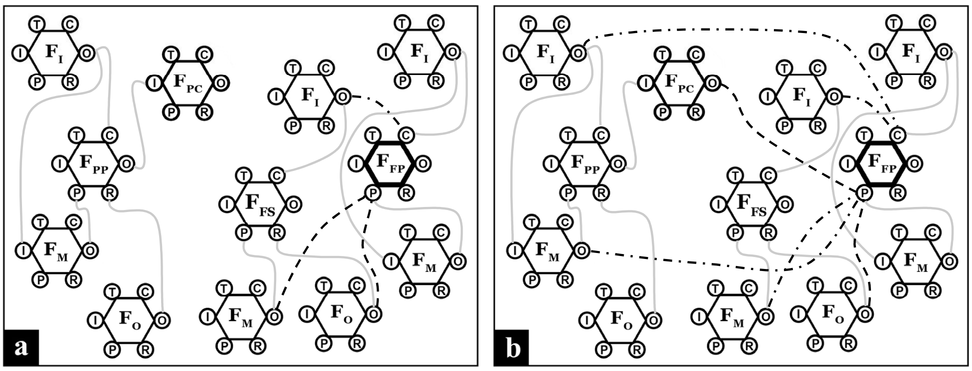

Figure 15, the identified negative (dash line) and positive (dash-dot line) impacts for Alternative B1 (a) and Alternative B2 (b). They grey lines connect the sub-functions to the associated core function.

5.5.7 Discussions and implications of the method

Comparison of Alternatives A1 and A2 shows that within the same scenario, the actual levels of safety provided in A2 can arguably be higher than A1 due to the provision of erosion protection. One may claim that some extra measures can prevent the erosion in A1. This is correct but the after-event maintenance required for Alternative A1 will be more extensive and costly compared to Alternative A2 anyway. Furthermore, the erosion protection offered by A2 improves the actual level of safety of the dike because an extra overtopping volume can be withstood by the dike compared to A1. In other words, the higher (actual) level of safety in A2 makes it more flexible since the investment for dike improvement, in the face of climate change, can be delayed longer than in A1. Moreover, the emergency inspections of the parking garage in A2 can have a positive impact on flood protection as well. Overall, the limited analysis of this paper shows that Alternative A2 has a better performance compared to Alternative A1. As opposed to the common belief in the Netherlands, it can be argued that constructing the parking within a short distance from the dike (as in Alternative A1), with a lower level of intended geographical dependency, is not necessarily safer than constructing a garage in the body of the dike (as in Alternative A2), with a higher level of intended geographical dependency.

Comparison of Alternatives B1 and B2 is not as straightforward as Alternatives A1 and A2. It can be seen that adding to the number of functions has considerably increased the complexity of the analysis. In Alternative B1, where the structures are loosely connected, the number of the potential dependencies is less than in Alternative B2. However, the negative impacts of a failing restaurant structure in Alternative B1 can be more serious than a car crash in Alternative B2. If so, Alternative B2 outperforms Alternative B1. This means that designing the parking garage and the restaurant in such a way as to have an intended contribution to flood protection, with a higher level of physical dependency, can even be better than a loose connection between them. Moreover, the support provided by the parking garage to the flood wall (via a shared wall) increases the flexibility of the system in two ways. First, the flood wall of Alternative B2 can be shorter than for Alternative B1. Second, future reinforcement of the flood wall can be done with fewer nuisances (from a technical point of view) in Alternative B2 than Alternative B1. Furthermore, the role of human actions in the success and failure of socio-technical systems is clearer in Alternative B2. On the one hand, the car crash, and failure in closing the windows of the restaurant are the human actions that can result in weakening the structural integrity of the flood wall. In contrast, the emergency inspections are also human actions that can increase the chance of detecting some failures of the flood wall, and therefore to act as a counter-balance to dampen human and technical malfunctioning. In short, it can be seen that, in addition to the technical performance of the system, human actions can have a very important role in the success and failure of the flood protection functions.

Concluding from the four alternatives, the higher levels of physical and geographical dependencies increases the number of potential dependencies, but not necessarily the number of negative impacts. The presence of various potential dependencies increases the complexity of the design considerations and the number of issues that need to be addressed in the design of the system. The identified negative impacts act as a signal that there needs to be something done in order to reduce the chance of the relevant potential dependencies being created or their impacts happening. In contrast, the positive impacts indicate the possibilities for improving the performance of the flood protection function that should be highlighted.

Despite the limitations of this analysis due to a lack of sufficient information and expert availability, the results of the functional analysis of the case study provide valuable insights for assessing the risks associated with multifunctional use of a flood defence, for prioritising the alternative designs, and for improving the capacity of a multifunctional flood defence to handle the unexpected situations. For example, with regard to selecting better performing design alternatives, it can be roughly said that the design alternative with more possibilities for improving than deteriorating the flood protection can be ranked higher than the other alternatives. Moreover, it can, for instance, be seen that Alternative B1 requires significant structural changes to the parking garage if the flood defence is to be reinforced in the future. This indicates that this alternative is not as flexible as the Alternative B2 to accommodate the sea level rise impacts in the future. On the other hand, the reinforcement of the flood defence can be easily achieved for Alternatives A1 and A2. Roughly, comparing the current flexibility of the alternative designs suggests that the designers should either choose for the Alternatives A1 and A2 that are better capable of handling the changes or to improve the design of the Alternatives B1 and B2 to enable ease of the reinforcement.

5.6 Conclusions

The present paper examined the use of the 'Functional Resonance Analysis Method (FRAM)' (Hollnagel and Goteman, 2004, Hollnagel, 2012) to the risk analysis of multifunctional flood defences. For the purpose of this research, FRAM is customised into five steps for describing, characterising and visualising the functions of a multifunctional flood system and their dependencies. FRAM is initially developed for retrospective safety assessment. The use of the method for prospective risk analysis of the built environment, in particular in the context of flood defences, has been done in the present paper for the first time. The objective of this paper is to enhance the risk analysis of multifunctional flood defences by developing a tool for outlining the scenario-based potential dependencies between the functional components of a multifunctional flood defence and their impacts.

The customised FRAM was applied in a case study to compare four generated alternative designs of a multifunctional flood defence. The analysis results demonstrated that the presence of a secondary structure in close vicinity of the flood defence can, indeed, impact the flood protection function. However, higher levels of physical and geographical dependencies do not necessarily weaken the flood protection function. Surprisingly, it was seen that locating a secondary structure in the dike body and or incorporating a secondary function into the flood protection function may even increase the coping capacity (flexibility) of the system to handle the unwanted situations.

While the customised FRAM approach is only applied to a single and quite specific scenario and system problem in this research, the proposed method seems promising for identifying the threats and opportunities associated with the design alternatives of multifunctional flood defences during the conceptual design phase. The method provides a qualitative tool for a broader view, analysis, and visualisation of many imaginable internal and external changes to the system including various types of human, technical system, and environment interactions. Furthermore, it provides a unified terminology and convenient framework to be used by the developers of multifunctional flood defences from different domains. Additionally, the results can also be used to facilitate identifying the possibilities for increasing the flexibility of the system to properly respond to various human and environmental induced unexpected events.

The proposed method, however, suffers limitations and needs further development. For example, the method should be supplied with quantified values of impacts that can be measured. Additionally, there is a need for guidelines for how to develop the scenarios and how much detail to include in the analysis. Furthermore, this paper takes the first step in using a cognitive method for systematic risk analysis of multifunctional flood defences. Using a more detailed analysis of multifunctional flood defences may result production of a large number of complicated graphs that are hard to interpret. Future empirical studies of the analysis are suggested to test the applicability of FRAM for detailed risk analysis in the case studies that are more complicated and data demanding.

6 Cost-effectiveness analysis of reinforcement strategies for multifunctional flood defences in the Netherlands[3]

"Complex problems have simple, easy to understand, wrong answers"
"In God we trust. All else show us the data"
Anonymous

6.1 Introduction

The Netherlands is a country where 60% of the land is prone to flooding from the North Sea, rivers or lakes. The country is currently protected against high water levels by a system of 53 uninterrupted flood defences. The flood defences comprise 3500 km of primary flood defences, which protect the country against its main sources of flooding, and 14000 km of secondary flood defences to prevent flooding from regional water systems. Such a sophisticated flood protection system is however not sufficient to maintain the safety of the Netherlands in the future.

It is anticipated that the frequency and intensity of extreme water levels is likely to increase due to climate change impacts. The consequences of flooding are also expected to become more severe as a result of continuous socio-economic developments (Ligtvoet et al., 2009, Aerts et al., 2013b, Alfieri et al., 2015). In anticipation of change, it can be well expected that the level of safety provided by the flood defences deteriorates progressively. This is especially the case in the coastal areas that are particularly vulnerable to rising sea water

[3] Anvarifar F., Kok, M., Thissen, W., D. Zevenbergen C., Osmanoglou, M. Raftari, B. 2017, Cost-Effectiveness Analysis of Reinforcement Strategies for Multifunctional Flood Defences in the Netherland, Journal of Critical Infrastructures [in press].

levels, resulting from climate change. The need for regular reinforcement, to ensure sufficient safety, is already well known in the Netherlands (Klijn et al., 2015b, Gersonius et al., 2016).

Development of such reinforcement strategies presents a dilemma. Reinforcement interventions are generally capital intensive and irreversible, placing a significant burden on national budgets. While early reinforcement can result in overinvestment, late reinforcement may lead to undesired losses in the future. It is currently possible to estimate changes to the risk of flooding for specific future scenarios (Ward et al., 2014). The likelihoods of these scenarios however are so uncertain that the Netherlands Royal Meteorological Institute (KNMI) deliberately does not specify the probabilities of their generated scenarios of sea level rise (Klein Tank et al., 2014). The challenge is, therefore, how to identify economically efficient reinforcement strategies, which explicitly address uncertainty about future circumstances in the process of development and assessment of such strategies (Van der Pol et al., 2015).

In the presence of uncertainty about future circumstances, the intention of the Dutch national water policy (the Delta Program) is to develop proactive flood protection strategies that link short term decisions to long term objectives (Rhee, 2012). This means to strike a balance between 'too much too early' and 'too little too late' investment strategies. The central goal is then to find the strategies that minimise the costs of flood protection over a long period of 50 to 100 years while maximising flexibility and maintaining sufficient safety (Kind, 2014, Van Alphen, 2015).

It has long being proposed in the Netherlands that the staged development of the dikes is a good way of maintaining safety while minimising the lifecycle costs of flood protection. Herein a dike refers to a man-made, earthen structure that is in place to protect the hinterland areas against flooding caused by high water levels in water bodies (sea, river, lake, or waterways) (TAW, 1998). After the disastrous flooding of 1953 in the Netherlands, Van Dantzig (1956) developed a model for finding optimal dike heightening investments. He assumed that continuous dike heightening (his theoretically preferred solution) is practically not feasible. In his model, he assumes a rather arbitrary choice for the reinforcement intervals. Among the many scholars who have tried to improve the model of Van Dantzig, Eijgenraam et al. (2012) have further enhanced the Van Dantzing model by improving the underlying assumptions about the likelihood of flooding. While the model of Eijgenraam et al. (2012) enables finding the optimal timing and height of the dikes, the provided solution minimises the lifecycle costs for only one scenario of future changes and for one specific discount rate.

Apart from the Dutch efforts, there is a growing body of global literature aimed at addressing uncertainty in the development and economic analysis of flood protection strategies more explicitly. The basic idea is to address uncertainty by increasing flexibility and embedding a learning potential into a reinforcement strategy (De Neufville, 2001, Li et al., 2007, Treasury, 2009, Gersonius et al., 2011). It is generally argued in the flood risk management literature that if flexibility exists to modify a reinforcement decision, (part of) the investment decisions can be delayed to a later time. This way, a dike is reinforced in stages such that the height of the dike and the reinforcement intervals can be modified based on how uncertainties unfold (Woodward et al., 2011, Linquiti and Vonortas, 2012). The possibility to change the course of action is referred to as 'managerial flexibility' (Triantis, 2003, Anvarifar et al., 2016), which is also adopted in this research. The opportunity to learn from the arrival of new information and the ability to revise investment decisions in the future makes flexibility a valuable attribute of a strategy (Linquiti and Vonortas, 2012).

Increasing the flexibility of a reinforcement strategy can be achieved in different ways. The most common approach presented in the literature is to reinforce a dike in predetermined time-steps. Although the reinforcement intervals (or the time-steps) are fixed, the decision makers have the flexibility to determine the required dike height based on past observations and future estimates of sea level rise (Scandizzo, 2011, Gersonius et al., 2011). Besides this approach, Linquiti and Vonortas (2012) suggest a different strategy in which the timing of reinforcement can be determined based on how sea water levels rise. Therefore, the reinforcement intervals (or the time-steps) are not predetermined, but they are variable as a function of changes in sea water levels. In both approaches, scenarios of sea level rise and different discount rates are applied to explicitly address uncertainty in the evaluation of the strategies. All of the mentioned studies conclude that addressing uncertainty by incorporating flexibility in the dike decision making (for both approaches) has the potential to provide significant economic benefits to long term flood risk management as well as to handle uncertainty. It is however acknowledged that the results are location-specific and sensitive to the assumptions about the evaluation model.

In the context of the Dutch flood risk management practice; there is a strong link between flood protection and land use development. Over time, provision of sufficient safety has attracted many people to live in the protected areas, leading to spatial developments in the close vicinity or even in the body of dikes (Stalenberg, 2010). As a result, many of the dike sections are multifunctional in a sense that they are used for other purposes in addition to their primary purpose of flood protection. Due to the complexities caused by multifunctional use of flood defences, maintaining the safety of these multifunctional dikes under changing conditions presents further challenges to the Dutch Government (Van Rijswick et al., 2015). While previous studies in the Dutch and global literature propose and evaluate staged dike reinforcement as a way of handling uncertainty, it is necessary to investigate whether staged dike reinforcement will also be advantageous in the context of *multifunctional* flood defences in the Netherlands.

Accordingly, the objective of this research is to examine to what extent increasing the flexibility of a reinforcement strategy can result in improved lifecycle cost-effectiveness, taking into account the other developments around a dike section. In doing so, two flexible reinforcement strategies are developed and evaluated in this research. Projections of sea level rise are used to address uncertainty about the sea level rise in the development and evaluation of the reinforcement strategies. Four discount rates are applied in this research to address this economic uncertainty as well. The cost-effectiveness analysis is examined in eight case studies of flood defences, representing different levels of development around the dikes in the Netherlands. The information from the project 'Water Safety in the 21st century' (in Dutch: 'Waterveiligheid 21e eeuw (WV21)') database (De Grave and Baarse, 2011) is used for the cost-estimates.

6.2 Methodology

Building upon prior studies presented in the flood risk management literature, two flexible reinforcement strategies are adopted and modified from Linquiti and Vonortas (2012). In these two strategies, flexibility manifests itself in the allocation of reinforcement intervals. Herein, a 'reinforcement interval' refers to the period of time within which a dike complies with its required safety standards. The terms 'design lifetime' and 'time-step' are also used in the present paper to indicate the reinforcement interval. A cost-effectiveness analysis is conducted to explore the value of flexibility embedded in these two strategies.

The cost-effectiveness analysis is carried out in two parts. First, the discounted lifecycle cost of each flexible strategy is compared to a baseline (inflexible) strategy. The computations are carried out for two scenarios of sea level rise. Eight case studies of mono-/multifunctional dikes are used to conduct this cost-effectiveness analysis. This part is aimed at exploring whether each flexible strategy is advantageous in handling sea level rise uncertainty compared to a baseline strategy, in every case study.

Second, the percentages of saved lifecycle costs are computed to compare the two flexible strategies against each other. The intention is to investigate whether one flexible study may perform better than the other. The comparative cost-effectiveness analysis is conducted in three selected cases among the eight case studies of Part One. In order to address the uncertainty about the discount rates, in addition to the sea level rise scenarios, four different discount rates are applied in the computations for this part. Further details of the methodology are described in the following sections.

6.2.1 The SLR scenarios

Sea level rise can be ranked as one of the most serious impacts of climate change on coastal areas (Nicholls and Klein, 2005, Robins et al., 2016). It is expected to contribute to intensifying the destructive power of storm surges, the rate of coastal erosion, and the intensity and likelihood of coastal flooding. Consequently, the damage caused by coastal flooding is also expected to increase significantly in the future (Bosello et al., 2012, Hinkel et al., 2014). Due to the uncertainty about the extent of sea level rise and its impact on coastal flooding, projections of sea level rise are used in the Netherlands for the development and assessment of flood protection strategies (Katsman et al., 2011).

In the same way, projections of sea level rise (Figure 17) as generated by KNMI in 2014 (Van Den Hurk et al., 2014) are applied here in order to develop and evaluate the reinforcement strategies in this paper. Accordingly, it is assumed that the sea water level along the Dutch coast will rise between a minimum of 25 cm (in the optimistic scenario) and maximum of 100 cm (in the pessimistic scenario) in 100 years from the time of the analysis (Figure 17). The upper and lower bounds of the sea level rise projections are applied for the development and evaluation of the strategies (Table 10). The term sea level rise is abbreviated as SLR throughout this paper.

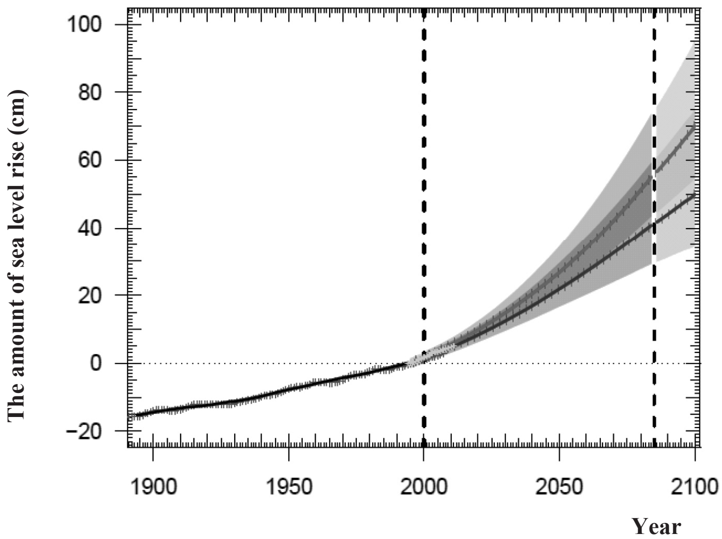

Figure 16, the projections of sea level rise in the North Sea coast (adopted from (Van Den Hurk et al., 2014))

Table 10, the upper (pessimistic) and lower (optimistic) bounds of sea level rise projections.

Scenario	Total sea level rise in 100 years
Low (optimistic scenario)	25 cm
High (pessimistic scenario)	100 cm

6.2.2 Dike height estimation for different scenarios

Even if a dike fulfils its required level of safety at the beginning of the analysis period, the actual level of safety provided by it deteriorates as the sea level rises. Therefore, coastal defences need to be reinforced in accordance with changes in sea water levels. In order to determine a relationship between the required extra height of the dike and the sea level rise, this research adopts the approach of Jonkman et al. (2013). They suggest that for a standard

Dutch coastal defence (a sea dike), the relationship between the required dike heightening (Δh) and the changes in sea water level (ΔSLR) can be described by Equation (1).

$$\Delta h = \Delta SLR * 2 \tag{1}$$

in which,
ΔSLR: the expected sea level rise in the time period of Δt (cm)
Δh: required additional dike height (cm)

Equation (1) determines the extra height of the dike required to compensate for the expected sea level rise of ΔSLR. In order to estimate the change in the sea level, the trend of sea level rise must be known. Currently, the rate of sea level rise is subject to uncertainty, and there is no evidence as to which trend might be closer to what will happen in the future (Wahl et al., 2013, Ezer et al., 2016). Hence, different linear and non-linear trends of future sea level rise have been proposed and applied in the literature (Woodward et al., 2011, Linquiti and Vonortas, 2012, Jonkman et al., 2013). For ease of analysis, a linear trend is applied in this research. Accordingly, it is assumed that the sea water level rises linearly over time towards the scenario-based projected sea level rise in 100 years (as sketched in Figure 17).

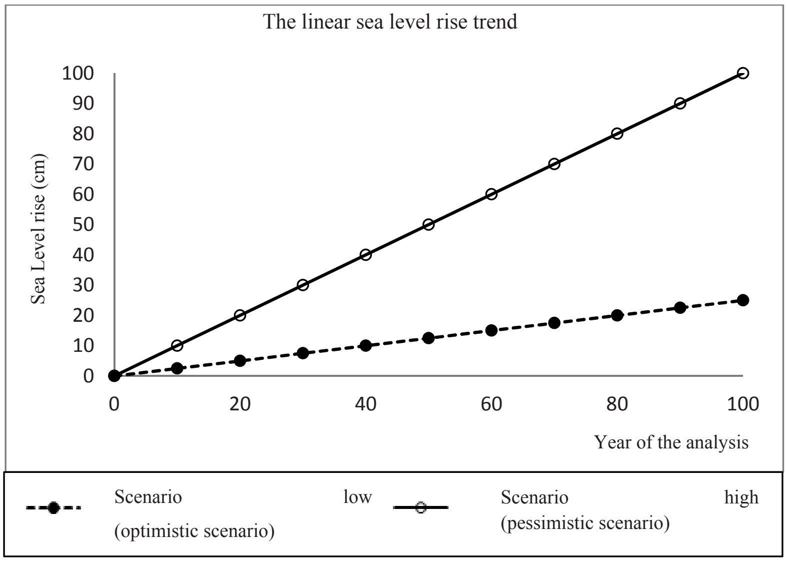

Figure 17, the linear trends of sea level rise in association with SLR scenarios

6.2.3 The strategies

Following the terminology of Linquiti and Vonortas (2012), two flexible strategies are applied in this research: these are called the 'predict & respond (Spr)' and 'sense & respond (Ssr)' strategies. Both strategies allow for staged dike reinforcement. The two strategies differ in the way the reinforcement intervals are determined. Besides these flexible strategies, a baseline strategy is also developed, which is considered to be inflexible. The strategies are described in the following sub-sections.

6.2.3.1 The predict & respond strategy (Spr)

The 'predict & respond' strategy is a flexible strategy that gives the decision makers the possibility to adjust their decisions on dike height at pre-determined time-steps. In this strategy, the reinforcement intervals (Δt) are fixed and constant in time, within the analysis period of 100 years.

It is assumed that the minimum level of safety, as set by the government, has to be maintained over this analysis period, independently of the SLR scenario. Therefore, a precautionary approach is applied. Therefore, we assume that the decision for the required height of the dike in the next reinforcement interval, Δt, is based on the most pessimistic SLR scenario for this interval. Subsequently, in the next decision making step, if the sea water level has risen by less than the prediction for the previous time interval, the dike is then raised by an equivalent amount to the maximum predicted sea level rise over the next time interval minus the extra level of safety provided by the dike at the time of decision making. Thus, decision makers have the flexibility to adjust their decision on the necessary height of the dike based on the observation of the sea level rise in the past in addition to the projection of sea level rise for the future. The decision making process is repeated in predetermined time-steps.

The 'predict and respond' strategy resembles the current practice of dike reinforcement in the Netherlands. In the traditional engineering practice in the Netherlands, a dike is normally designed for the design lifetime of 50 year (Eijgenraam, 2009). Eijgenraam et al. (2012) estimate that the optimal reinforcement intervals for river dikes in the Netherlands should be in the order of 40 to 60 years. This estimate is, however, only based on one scenario of sea level rise. In other research, Linquiti and Vonortas (2012) apply a reinforcement interval of

20 years while Woodward (2012) uses intervals of 30 years. Reinforcement intervals of less than 10 years have also been reported in the flood risk management literature (Rijnland-Water-Board, 2009).

The use of one scenario as in the Eijgenraam et al. (2012) model does not address the uncertainty in sea level rise. It is however practical as a first step to explore how the choice of reinforcement interval can impact the cost-effectiveness. Taking into account the previous studies, three different reinforcement intervals (Δt) of 10, 20, and 50 years are explored in this research. The associated 'predict & respond (Spr)' strategies are abbreviated as, respectively: Spr10, Spr20 and Spr50. The number following each 'Spr' strategy represents the associated reinforcement interval. Table 11, shows the estimated ΔSLR in association with each of the strategies Spr10, Spr20, and Spr50 in both SLR scenarios. Since a linear SLR trend is applied in this research, the required dike heights (Δh) for each Spr appear to be the same for each interval in 100 years of analysis.

6.2.3.2 The sense & respond strategy (Ssr)

The 'sense & respond' strategy gives the decision makers the flexibility to reinforce the dike at any year. This way, the dike is reinforced when the sea water level rises to the amount of a pre-specified ΔSLR threshold value.

In the 'sense & respond' strategy, the observation of sea level rise in the past is used to decide whether the dike needs to be reinforced. Hence, there is no need to specify sea level rise for a forthcoming period of time. Furthermore, this strategy provides the decision maker with the flexibility to take action at any time. Therefore, a precautionary approach as applied in the 'predict and respond' is not needed.

In the beginning of the analysis (year 0) the dike is raised twice the amount of a pre-specified ΔSLR. The dike is raised again, at any time, when the sea water level rises to ΔSLR. In this way, sufficient safety is proactively maintained. Since the reinforcement time-steps (Δt) can become shorter or longer, depending on the evolution of sea level rise, the lengths of reinforcement intervals (and the design lifetime) are variable. Correspondingly, the total number of reinforcement practices in 100 years will depend on the choice of ΔSLR threshold as well as the SLR scenario. For example, the reinforcement intervals (Δt) will be shorter for the pessimistic scenario of sea level rise compared to the optimistic scenario and therefore the number of reinforcement practices will be higher. In accordance to the two SLR scenarios, the reinforcement intervals for Ssr can vary between a minimum value (associated with the high SLR scenario) and a maximum value (associated with the low SLR scenario).

Linquiti and Vonortas (2012) and Hoekstra and Kok (2008) make a rather arbitrary choice and use the ΔSLR threshold value of 50 cm. It can be expected that the cost-effectiveness of a strategy may vary based on the choice of ΔSLR threshold. To investigate this, this research chooses to examine the cost-effectiveness of the 'sense & respond' strategy for a range of ΔSLR threshold values. In accordance with the projection of sea level rise in 100 years, three ΔSLR threshold values of 10cm, 25cm, and 50 cm are selected and examined in this research. The associated 'sense & respond (Ssr)' strategies are abbreviated as, respectively, Ssr10, Ssr25 and Ssr50. Table 11 shows the estimated reinforcement intervals (Δt) for each one of Ssr10, Ssr25, and Ssr50 in both scenarios of sea level rise. The number following each 'Ssr' strategy represents the associated ΔSLR threshold. Since a linear SLR trend is applied in this research, the reinforcement intervals for each Ssr appear to be the same at each intervention moment in the 100 years of analysis.

Table 11, the attributes of 'Predict & respond (Spr)' and 'Sense & respond (Ssr)' strategies

Predict & respond strategy (Spr)				
Name of the strategy		Spr10	Spr20	Spr50
Reinforcement intervals (Δt)		10 years	20 years	50 years
ΔSLR in the end of each Δt	Optimistic scenario (Low)	2.5 cm	5 cm	12.5 cm
	Pessimistic scenario (High)	10 cm	20 cm	50 cm
Sense & respond strategy (Ssr)				
Name of the strategy		Ssr10	Ssr25	Ssr50
Sea level rise threshold (ΔSLR)		10 cm	25 cm	50 cm
Reinforcement intervals (Δt) associated with each ΔSLR	Optimistic scenario (Low)	40 years	100 years	100 years
	Pessimistic scenario (High)	10 years	30 years	50 years

6.2.3.3 *The baseline strategy*

Commonly, a ‘do nothing’ strategy is developed and applied in the academic literature as a baseline strategy for the purpose of comparative economic analysis (Woodward et al., 2011, Linquiti and Vonortas, 2012). In the context of flood risk management, the ‘do nothing’ strategy represents the situation in which the decision makers choose not to invest in reinforcement. Consequently, the rising sea water level will result in flooding events, which cause extra damage in the considered case studies. In this situation, the economic analysis needs to address both the costs of flood control as well as the benefits of damage prevention in order to evaluate a strategy. This approach has already been applied by most of the researchers who have evaluated flexibility in reinforcement decision making (Woodward et al., 2011, Scandizzo, 2011, Linquiti and Vonortas, 2012).

In this research, a cost-effectiveness analysis is carried out assuming that the dike section under study has to maintain a required level of safety in between two reinforcement practices. The benefits associated with providing extra safety, or the lack of a certain amount of safety is not taken into account. Therefore, instead of using the ‘do nothing’ as baseline, a different baseline strategy is developed and applied. The baseline strategy of this paper is based on the pessimistic scenario of sea level rise in which the dike must be safe enough to resist the highest amount of sea level rise (100 cm over the analysis period of 100 years). In this strategy, the decision for the reinforcement of the dike is fully specified and implemented in the first year of a 100 year analysis period. In this year (year 0) the dike is raised to twice the amount of the highest expected sea level rise in 100 years, which is 200 cm. The baseline strategy is considered to be inflexible since the possibility to change the dike during the 100 year period is not taken into account.

Principally, in the three strategies of the research it is assumed that the first reinforcement occurs in the first year of the 100 year analysis. The differences between the strategies are schematised in Figure 18. It can be seen that the baseline strategy represents only one reinforcement stage in the beginning of the analysis period (Y0). For the Spr and Ssr strategies, the reinforcement intervals Δt and the added height of the dike Δh change as follows. For each Spr, $\Delta t_1 = \Delta t_s = \ldots = \Delta t_n$, but Δh will depend on the observations of sea level rise in the previous periods as well as the most pessimistic projection of the ΔSLR for the next period of Δt . For each Ssr, Δt can vary depending of the rate of sea level rise, but at the moment that sea water level reaches a predetermined ΔSLR, the dike is raised to the amount of Δh (= 2*ΔSLR). Therefore, for Ssr, $\Delta h_0 = \Delta h_1 = \ldots = \Delta h_n$.

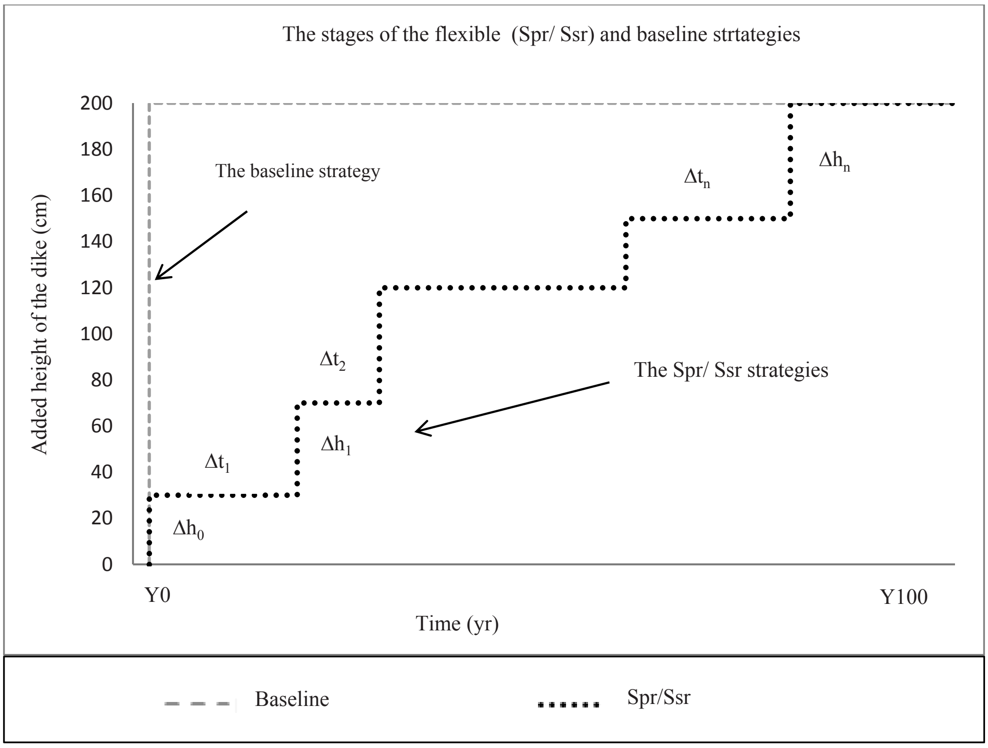

Figure 18, the schematization of the baseline, Spr and Ssr strategies. For each Spr, $\Delta t_1 = \Delta t_2 = \ldots = \Delta t_n$, but Δh varies. For each Ssr, $\Delta h_0 = \Delta h_1 = \ldots = \Delta h_n$, but Δt varies.

6.2.4 The evaluation model

Evaluating the economic performances of flood protection strategies is a key component of decision support in flood risk management (De Bruin et al., 2014). In the Netherlands, the popular evaluation approaches are based on cost benefit analysis or cost effectiveness analysis (Klijn et al., 2015a). This research chooses to apply cost-effectiveness analysis to investigate the value of managerial flexibility embedded in reinforcement strategies. Similar to the model assumption of Kind et al. (2014), it is assumed that every dike section has to comply with the safety standards. This level of safety is required to be maintained even in the face of sea level rise. Hence, the potential benefits of reducing the flood consequences provided by implementing the two flexible strategies are not taken into account. The measure of effectiveness is, therefore, the discounted lifecycle cost of each strategy, which is computed by the sum of the discounted reinforcement costs over the analysis period of 100 years. The analysis period is chosen to be 100 years in accordance with the Dutch standards presented at 'Flood Policy Document' (in Dutch: 'Beleidsnota Waterkeringen') (Morreau, 2009).

The reinforcement costs of the strategies are calculated with the use of an exponential cost function presented by Equation (2). This cost function was initially developed by Kind (2011) and has already been applied in several studies for finding the optimal dike heightening strategies in the Netherlands (Eijgenraam et al., 2012, Eijgenraam et al., 2014, Kind, 2013, De Grave and Baarse, 2011). The reinforcement investment cost is computed as:

$$\text{Investment cost}: I_{(\Delta h)} = (f + v * \Delta h) * e^{(\Delta h * \lambda)} \quad (2)$$

in which,

$I_{(\Delta h)}$: reinforcement cost of adding the height of Δh for 1km of a dike section (M€/km)

Δh: required additional dike height to maintain safety (cm)

f: fixed cost coefficient for 1km of a dike section (M€)

v: variable cost coefficient for 1km of a dike section (M€/cm)

λ: scale parameter (1/cm)

In Equation (2) the reinforcement cost consists of a fixed part (f) and a part that varies (v) based on the added height of the dike. Generally, the value of the coefficients f, v, and λ will depend on the type of the reinforcement measure to be applied in a specific case.

It is generally desired in the Netherlands to reinforce dikes with minimum possible disturbance of the dike's surroundings (De Bruin et al., 2014). As a result, simple heightening and widening of a dike cannot be practiced where there is another object around the dike. In such a situation, more complicated reinforcement measures are carried out in order to create fewer disturbances to the secondary function(s) of a multifunctional dike. De Grave and Baarse (2011) propose three types of reinforcement measures that can be used in different situations. In the first case, the dike is simply widened and heightened as shown in Figure 20a, where there is sufficient space available around the dike. If the area around the dike has been developed such that there is only a small distance between the dike and the secondary function, which is not sufficient for widening the dike, the dike is then reinforced via the use of the measures as presented in Figure 20b. Finally, if the secondary functions are currently a part of dike body, then more sophisticated measures (e.g. coffer dams) are used since there is no space around the dike for widening it (Figure 20c).

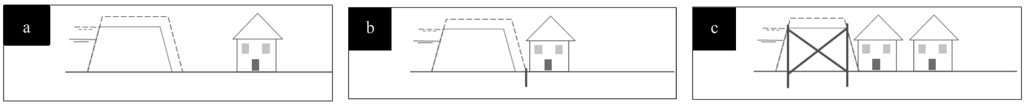

Figure 19, the three types of reinforcement measures for multifunctional dikes (adopted and modified from De Grave and Baarse (2011)).

In each flexible strategy, the reinforcement investments are made at several times in the future. In accordance with the usual practice in cost-benefit analysis, the present value of aggregated life cycle costs on an ex-ante basis is computed by Equation (3) in which the parameter r denotes the discount rate.

$$\text{Discounted life cycle costs} = \sum_{t=1}^{100} I_{(\Delta h(t))} * \frac{1}{(1+r)^t} \tag{3}$$

in which,

$I_{(\Delta h)}$: reinforcement cost of adding the height of Δh for 1km of a dike section (M€/km)

Δh (t): required additional dike height to maintain safety at the time of decision making (cm)

r: discount rate

t: the time of reinforcement (year)

The costs incurred from the year 100 onwards are not addressed in this research. Moreover, it is assumed that the coefficients of the cost function for each specific reinforcement measure remain identical at every stage of the reinforcement.

6.2.5 The analysis process

In order to address the research objective, the cost-effectiveness analysis is conducted in two parts.

In the first part of the analysis, the discounted lifecycle cost of each Spr and Ssr reinforcement strategy is compared to the baseline strategy separately. Each strategy is examined in two SLR scenarios. The intention is to explore whether the managerial flexibility embedded in the Spr and Ssr strategies is more cost-effective than the baseline. The results are also used to explore whether the embedded managerial flexibility in each strategy is useful for handling sea level rise uncertainty, in the context of multifunctional dikes. A discount rate of 3% is selected for analysis, which is identical to those applied in Gersonius et al. (2013) and Woodward (2012).

The second part of the analysis is designed to compare the two ‘sense & respond’ and ‘predict & respond’ strategies. The intention is to explore whether one of them is more cost-effective in the context of mono-, resp. multifunctional dikes. To do this, the percentage of saved life cycle costs is computed for each flexible strategy. The computed saved lifecycle costs demonstrate the economic advantage of each strategy compared to the baseline strategy. For each flexible strategy, the percentages are computed by Equation (4).

$$\text{Saved lifecycle costs} = \left(1 - \sum_{t=1}^{100} \frac{I_{(t)}}{I_{(Baseline)}} * \frac{1}{(1+r)^t}\right) * 100 \qquad (4)$$

in which,

$I_{(t)}$: reinforcement cost in year t (M€/km)

$I_{(Baseline)}$: reinforcement cost of the baseline strategy (M€/km)

r: discount rate

t: the time of reinforcement (year)

The choice of the discount rate to be applied for the economic analysis of climate adaptation strategies is currently under debate by many scholars (Stern, 2006, Goulder and Williams III, 2012, Millner et al., 2013). For instance, Stern (2007) suggests that a low discount rate is necessary to prevent discounting the future, as a fair approach to future generations. In the global flood risk management literature, Woodward et al. (2011) apply two discount rates of 1.4% and 3.5%. Linquiti and Vonortas (2012) use the discount rates of 3% and 7%. Dutch researchers have used different discount rates ranging from 1% to 5.5% (Jonkman et al., 2009, Gersonius et al., 2011, Kind, 2014). In order to include the uncertainty about the discount rate, four discount rates of 1%, 3%, 5%, and 7% are applied in the second part of the analysis

6.3 Case studies

The Netherlands is currently protected by a system of 53 enclosed flood defences comprising dikes, dunes, sea walls, dams and storm surge barriers. The enclosed dike systems are called the 'dike rings'. As shown in Figure 21, each enclosed area (a dike ring) is specified with a number. Each dike ring comprises several dike sections which might be different in their structural characteristics (e.g. cross section or material). Each dike section considered in the case study is part of a sea dike. As defined by the Technical Advisory Committee on Water Defences in the Netherlands (TAW), a 'sea dike' refers to an earthen structure that is designed to resist high water levels and wave attack during extreme events in the coastal areas (TAW, 1998).

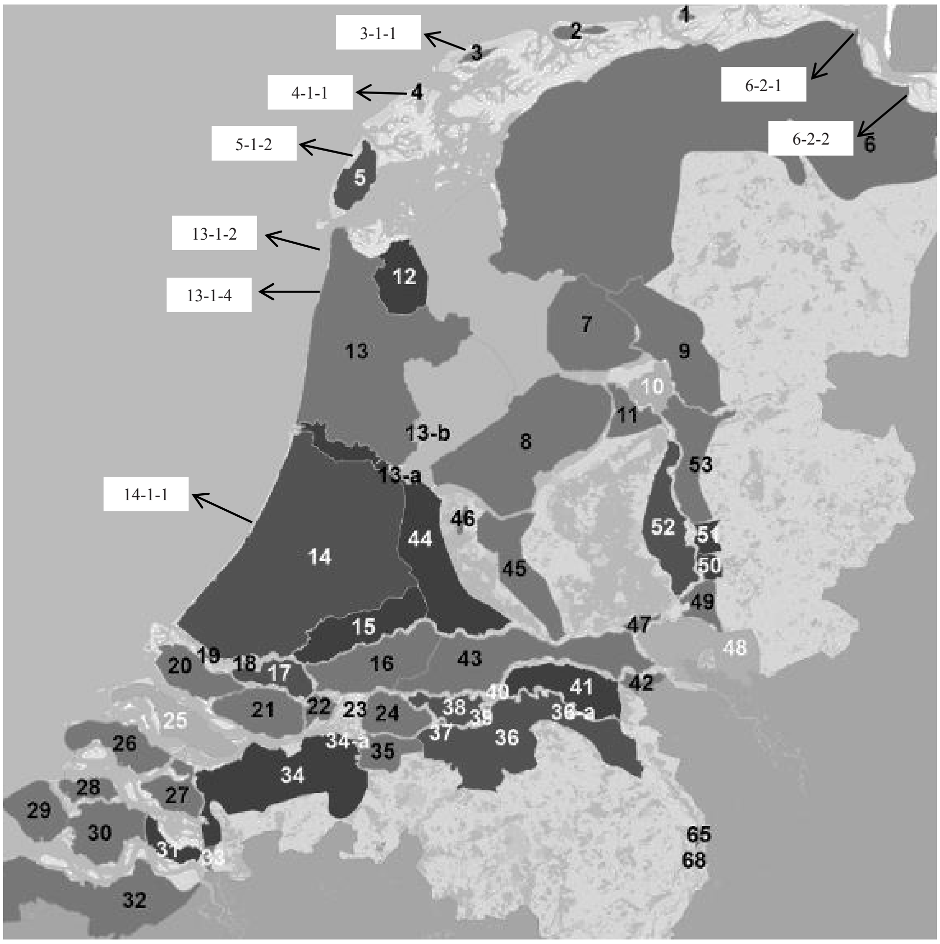

Figure 20, Locations of the eight case studies as modified from VNK (2012)

Over time, the protected inland areas, in particular along the North Sea, have been extensively developed and urbanised. As a result, there are many dike sections in the Netherlands that are used for other purposes (housing, industry, transportation, etc.) in addition to their primary purpose of flood protection. The presence of other objects in the vicinity of a dike makes it difficult to reinforce the dike. As the available space between the dike body and the secondary function of a dike decreases, more sophisticated (and costly) reinforcement measures have to be implemented.

Eight cases of mono-/multifunctional dike sections are used in the analysis of this research. All the necessary information about the case studies is extracted from the database of De Grave and Baarse (2011). The chosen dike sections belong to the dike rings 3, 4, 5, 6, 13, 14, all of which are located in the coastal areas of the Netherlands. Figure 21 shows the locations of the selected dike sections along the North Sea in which each dike section is identified by a 'section code'. Table 12 represents the names of the chosen dike sections and the associated cost function parameters.

Table 12, cost function parameters for the eight case studies from De Grave and Baarse (2011)

Location	**Section code**	**λ (1/cm)**	**f (M€)**	**v (M€/cm)**
Waddenzeedijk Texel	5-1-2	0.00336	16.61	0.67
Vlieland local dike	4-1-1	0.00336	3.79	0.03
Den Helder Havendijk	13-1-2	0.00336	34.7	0.0
Location	**Section code**	**λ (1/cm)**	**f (M€)**	**v (M€/cm)**
Waddenzee kering Terschelling	3-1-1	0.00095	0.5	0.75
Eems-Dollard	6-2-2	0.00095	32.14	1.29
Eems-Dollard kust	6-2-1	0.00095	74.98	2.92
Hondsbossche Zeewering	13-1-4	0.00095	14.4	0.17
Zeewering Zandvoort-Bloemendaal	14-1-1	0.00095	53.77	0.02

For each dike section, the choice of reinforcement measure is based on the availability of space between the dike and its secondary function(s). This space availability and the associated reinforcement measure are reflected in the estimation of fixed and variable costs in the database. Accordingly, the ratio of fixed over variable costs (f/v) is used to group the dike sections in three classes. For ease of referral, the term 'level of development' is used in this research to address these three classes as follows.

- Low level of development: represents a monofunctional dike, where there is no secondary object in the close vicinity of the dike, throughout the dike section. There is enough space available for normal dike reinforcement as shown is Figure 20a. The ratio of fixed over variable costs (f/v), as shown in Table 13, is the lowest for this class.
- Medium level of development: represents a multifunctional dike, where there are some secondary functions located around the dike. The locations of these objects mean that there is still some space available for reinforcement, but not enough for dike widening. Therefore, more expensive reinforcement measures (Figures 20b) are required at the locations of these secondary objects. The ratio of (f/v) lies in between the two other classes (Table 13).
- High level of development: represents a multifunctional dike, where there are some secondary functions located in the dike body. This situation is very common in densely urbanised areas. Due to lack of space, often the only possibility for dike reinforcement is to apply more sophisticated and expensive types of reinforcement measures as illustrated in Figure 20c. The ratio of (f/v) is the highest for this class (Table 13).

In the database, two scale parameters are given for the chosen eight case studies. Therefore, Table 13 is divided into two parts in association with the two different values of the scale parameter λ. For ease of referral, a set of abbreviated codes ('L' and S' codes) have been assigned to each dike section, where 'L' codes show the selected cases with λ= 0.00336 and 'S' codes show the cases with λ= 0.00095.

Table 13, the cases studies specifications

	λ:0.00336					λ:0.00095				
Development level	**Section code**	**Abbreviation**	**f M€**	**v M€/cm**	**f/v cm**	**Section code**	**Abbreviation**	**f M€**	**v M€/cm**	**f/v cm**
Low level of development	**5-1-2**	L1	16.61	**0.67**	**25**	**3-1-1**	S1	0.5	0.75	0,67
						6-2-2	S2	32.14	1.29	24,9
						6-2-1	S3	74.98	2.92	25,7
Medium level of development	**4-1-1**	L2	3.79	**0.03**	**126**	**13-1-4**	S4	14.4	0.17	84,7
High level of development	**13-1-2**	L3	34.7	**0.0**	**N/A***	**14-1-1**	S5	53.77	0.02	2688.5

** In this case, the variable cost is estimated to be nearly zero, meaning that the ratio of fixed over variable cost becomes very big.*

Furthermore, for the sake of consistency and ease of analysis, it is assumed that the dike profile is the same along the dike section for all the cases studies and follows the standard sea dike profile as described in Jonkman et al. (2013). For the computations, the length of the dike section is assumed to be 1km in all cases. As also applied by De Grave and Baarse (2011), it is assumed that the same cost function (Equation 2) can be applied to every case study.

6.4 Results and discussions

This section presents the results of the analysis in two parts. First, the discounted lifecycle costs of the flexible strategies 'predict & respond' and 'sense & respond' are compared to the baseline strategy. The results for each flexible strategy are presented and discussed separately.

Second, the percentages of discounted lifecycle costs of the flexible strategies 'predict & respond' and 'sense & respond' are presented, as computed for each SLR scenario and for the four discount rates. The implications of the analysis are discussed in the end of each part.

6.4.1 Part 1: valuing flexibility in each strategy

In this section, first, the discounted lifecycle costs of the ‘predict & respond (Spr)’ strategy for Spr10, Spr20 and Spr50 are summarised in Table 14 and sketched in Figure 22. Second, the discounted lifecycle costs of the ‘sense & respond (Ssr)’ strategy for Ssr10, Ssr25, and Ssr50 are summarised in Table 15 and sketched in Figure 23.

In Table 14, presents columns of results presented for each Spr (for every reinforcement interval). The left column shows the results for the low SLR scenario while the right column shows the results for the high SLR scenario. The results for the baseline strategy are shown in a single column because the baseline strategy is only based on the high SLR scenario.

Table 14, the discounted life cycle costs for the ‘predict & respond (Spr)’ and baseline strategies for a discount rate of 3%

Strategy: ‘predict & respond’ ’ Discount rate: 3%			Lifetime: 10 years (Spr10)		Lifetime: 20 years (Spr20)		Lifetime: 50 years (Spr50)		Lifetime: 100 years (baseline)
Section Code	Abbr.	λ (1/cm)	Discounted lifecycle costs (M€/km)		Discounted lifecycle costs (M€/km)		Discounted lifecycle costs (M€/km)		Discounted lifecycle costs (M€/km)
			Low	High	Low	High	Low	High	All scenarios
5-1-2	L1	0.00336	90	119	81	105	125	144	295
4-1-1	L2	0.00336	16	17	11	12	11	12	19
13-1-2	L3	0.00336	133	137	81	84	57	60	68
3-1-1	S1	0.00095	30	59	45	67	88	102	182
6-2-2	S2	0.00095	169	219	146	185	192	218	351
6-2-1	S3	0.00095	391	504	334	423	438	496	797
13-1-4	S4	0.00095	60	67	41	47	39	42	59
14-1-1	S5	0.00095	202	205	118	120	74	75	70

In the ‘predict and respond’ strategy, at the end of each reinforcement interval, the sea level may have risen differently than predicted at the beginning of that reinforcement interval. Therefore, at the end of each reinforcement interval, the decision for the next interval is assumed to be made based on the observation of sea level rise in the previous interval and the prediction of the sea level rise for the next interval. Because a precautionary approach is presumed, prediction of sea level rise is based on the high scenario, and the required extra height needs to be adjusted when a lower sea level rise has been observed. This means that, depending on the choice of the reinforcement interval, a large combination of low and high scenarios may occur over the analysis period of 100 years. In fact, the discounted lifecycle costs for the various combinations of the scenarios will vary between a minimum and a maximum value. The minimum discounted lifecycle cost is incurred when the decision makers constantly observe the low rate of sea level rise during the 100 years. The maximum discounted lifecycle cost corresponds to the occurrence of the high scenario of sea level rise during the same time. Rather than presenting the computations for the whole range of possible combinations of ∆SLR, the applied discounted lifecycle costs in this research only present the full occurrence of the two extreme SLR scenarios.

At first glance, it can be seen in Table 14 that for each scenario, in some cases (e.g. S1) the discounted lifecycle costs increases as the reinforcement interval increases, while in other cases (e.g. S4) the discounted lifecycle costs decrease by raising the reinforcement interval. In order to further explore the results, they are plotted per case study type in Figure 22.

For all four cases of monofunctional dikes (L1, S1, S2 and S3 in Figure 22a), the discounted lifecycle costs for all of Spr10, Spr20 and Spr50 seem to be lower than the baseline strategy. In the low SLR scenario, the Spr10 and Spr20 strategies seem to be cheaper than the Spr50. However, all of the discounted lifecycle costs become higher for the high SLR scenario, but they remain lower than for the baseline strategy. Among the different reinforcement intervals considered, the Spr20 (with time-steps of 20 years) shows the lowest discounted lifecycle cost. This is because of the higher number of reinforcement practices for Spr 10 and the higher value of the initial reinforcement costs for Spr50. Furthermore, the lifecycle costs are much lower in the case of S1, where the fixed costs are much lower than the other cases. Generally, it can be said that, providing the decision makers with managerial flexibility to adjust their decisions in predetermined time-steps seems to be advantageous (cost-effective) for monofunctional

In Figure 22b, L2 and S4 represent the medium level of development (with the middle f/v ratio) while L3 and S5 represent the high level of development (with the highest f/v ratio) around the dike. Firstly, it is seen that the computed lifecycle costs are remarkably lower for these multifunctional dikes (L2, S4, L3, S5) compared to the results for the monofunctional dikes (L1, S1, S2, S3). This is because the variable costs (in the database) for the multifunctional dikes are much lower than for the monofunctional dikes. Consequently, the contribution of the variable costs to the overall lifecycle costs is much lower for multifunctional dikes than for monofunctional dikes.

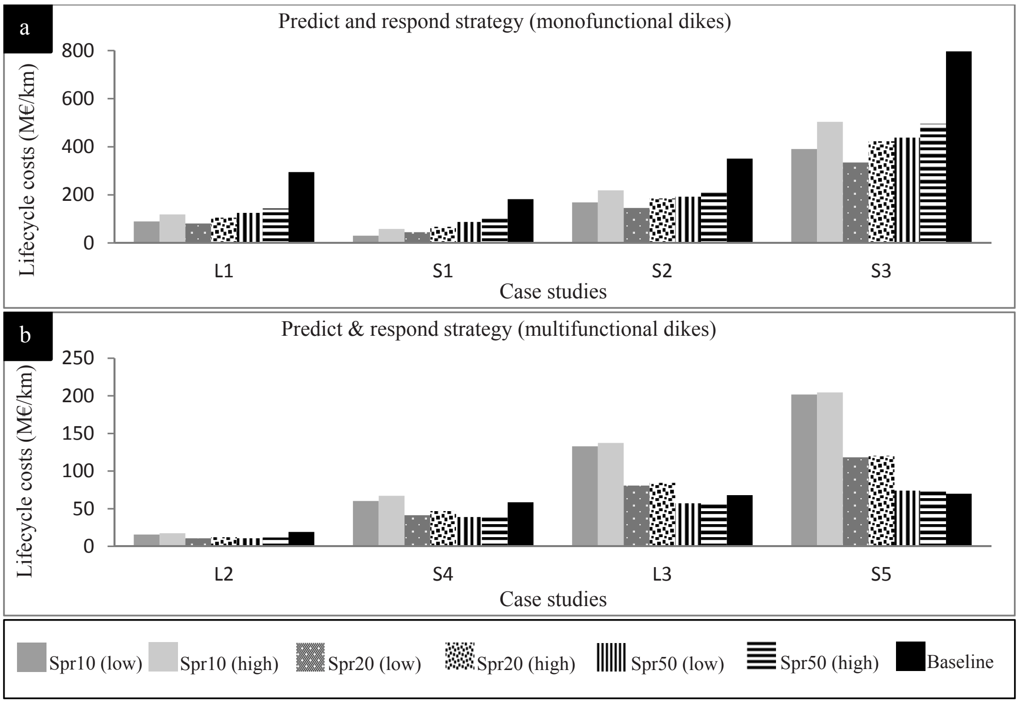

Figure 21, the discounted lifecycle costs for the strategy ‘predict & respond (Spr)’ and the baseline strategy for reinforcement intervals of 10years (Spr 10), 20 years (Spr 20), and 50 years (Spr 50) in low and high SLR scenarios and for a discount rate of 3%. (a) Represents the results for the monofunctional dikes and (6) shows the results for the multifunctional dikes.

Secondly, the Spr10 and Spr20 seem to be more expensive than the baseline, in particular for the cases L3 and S5 with the highest ratio of f/v. Except for the case of S5 (representing a highly urbanised area), for the other three cases (L2, S4, L3) the discounted lifecycle costs of Spr50 are slightly lower than the baseline. Furthermore, the differences between the lifecycle costs of Spr strategies and the baseline are notably lower for multifunctional dikes (Figure 22b) compared to monofunctional dikes (Figure 22a). Roughly, the time-steps of 50 years shows more promising results for multifunctional dikes, in particular for L2 and S4. Overall, the results indicate that the managerial flexibility to adjust the reinforcement decision in several stages is less valuable for the (existing) multifunctional dikes than for monofunctional dikes.

The second set of the results (Figure 23 and Table 15) represent the discounted lifecycle cost computations for the 'sense & respond (Ssr)' and baseline strategies. Two columns of results are computed for every Ssr (for every considered ΔSLR). The left column represents the results for the low SLR scenario while the right column shows the results for the high SLR scenario. Similarly to Table 15, the results for the baseline strategy are shown in one column.

In every case study (as shown in Table 15), the discounted lifecycle costs of Ssr10, Ssr25, and Ssr50 vary remarkably between the two SLR scenarios. This is related to the lower number of reinforcement practices required in the low SLR scenario compared to the high SLR scenario. Furthermore, in the low SLR scenario, the life cycle costs of Ssr seem to be more cost-effective than the baseline for almost all the ΔSLR considered and in almost all cases. This is however not the case for the high SLR scenario.

Table 15, the discounted life cycle costs for the 'sense & respond (Ssr)' and the baseline for the discount rate of 3%

Strategy: 'sense & respond' Discount rate: 3%			Lifetimes: 10 to 40 years (Ssr10)		Lifetimes: 30 to 100 years (Ssr25)		Lifetimes: 50 to 100 years (Ssr50)		Lifetimes: 100 years (baseline)
Section Code	Abbr.	λ (1/cm)	Discounted lifecycle costs (M€/km)		Discounted lifecycle costs (M€/km)		Discounted lifecycle costs (M€/km)		Discounted lifecycle costs (M€/m)
			Low	High	Low	High	Low	High	All scenarios
5-1-2	L1	0.00336	45	119	59	100	117	144	295
4-1-1	L2	0.00336	7	17	6	11	10	12	19
13-1-2	L3	0.00336	52	137	41	69	49	60	68
3-1-1	S1	0.00095	22	59	40	67	83	102	182
6-2-2	S2	0.00095	83	219	101	170	177	218	351
6-2-1	S3	0.00095	190	504	232	389	404	496	797
13-1-4	S4	0.00095	25	67	24	40	35	42	59
14-1-1	S5	0.00095	77	205	57	96	61	75	70

For monofunctional dikes, in the cases L1, S1, S2, and S3 in Figure 23a, the discounted lifecycle costs for all chosen ΔSLR thresholds are significantly lower than for the baseline strategy. In the low SLR scenario, the discounted lifecycle costs for the Ssr10, Ssr25 seem to be lower than Ssr50. The Ssr10 shows the lowest lifecycle costs in the low SLR scenario whilst Ssr25 seems to have the lowest lifecycle costs in the high SLR scenario. Due to the presence of sea level rise uncertainty, it does not seem possible to determine which ΔSLR threshold is the most cost-effective. Yet, it can be seen that providing the decision makers with managerial flexibility to reinforce the dike at any year seems to be advantageous (cost-effective) for monofunctional dikes.

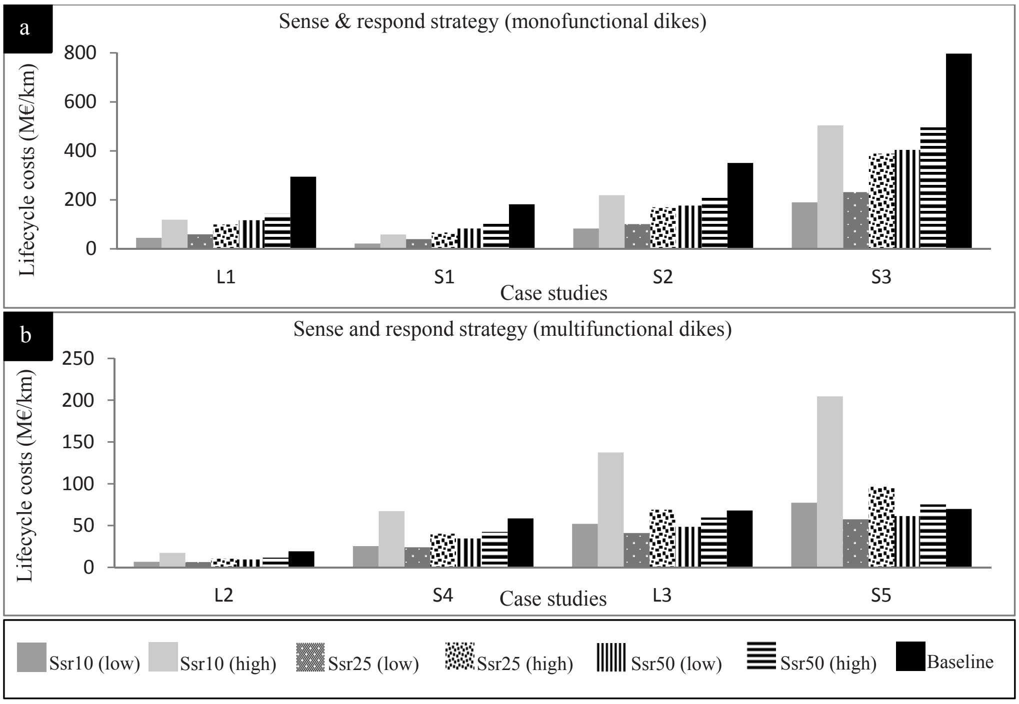

Figure 22, the discounted lifecycle costs for the strategy 'sense & respond (Ssr)' and the baseline strategy for the ΔSLR thresholds of 10 cm (Ssr 10), 25 cm (Ssr 25), and 50 cm (Ssr 50) in low and high SLR scenarios and for a discount rate of 3%. (a) Represents the results for the monofunctional dikes and (b) shows the results for the multifunctional dikes.

For multifunctional dikes, in the cases L2, S4, L3, and S5 in Figure 23b, the discounted lifecycle costs are generally of the same order of magnitude as in the baseline strategy. If the high scenario of sea level rise happens, the discounted lifecycle costs for Ssr10 and Ssr25 can become even higher than for the baseline strategy. The discounted lifecycle costs for Ssr50 however remain a bit lower than the baseline, except for the highly urbanised case of S5. In the low SLR scenario, the Ssr strategy (for every considered ΔSLR) has a lower discounted lifecycle cost compared to the baseline. This is because the number of reinforcement practices is significantly lower for the low scenario of sea level rise compared to the high scenario. Overall, the results for Ssr10, Ssr25, and Ssr50 are very much scenario dependent. Generally, the results indicate that having the managerial flexibility to adjust the reinforcement decisions at any year (determined based on ΔSLR) can be less valuable for the (existing) multifunctional dikes.

In conclusion, it can be seen that enabling managerial flexibility in both ways (in fixed time-steps or based on fixed ΔSLR) is indeed valuable and advantageous for monofunctional dikes. This conclusion is consistent with the results of previous case studies in the UK (Woodward et al., 2011) and developing countries (Scandizzo, 2011, Linquiti and Vonortas, 2012). Such a conclusion is not necessarily valid for multifunctional dikes, especially when the ratio of f/v rises.

Furthermore, it is observed that the choice of reinforcement interval/ΔSLR threshold significantly impacts the lifecycle costs in different SLR scenarios. This is because it is not only the amount of required dike height (Δh), but also the number of reinforcement practices in 100 years that changes in each SLR scenario. In the presence of sea level rise uncertainty, this observation clearly indicates that any attempt to determine the best timing of reinforcement based on only one scenario can be incorrect. Additionally, it can be well expected that developing and evaluating the reinforcement strategy based on solely one extreme scenario may result in overinvestment if a lower sea level rise occurs in the future.

Besides that, the results vary noticeably depending on case specific cost estimations and the ratio of (f/v). This observation clearly demonstrates that it is of utmost importance to take the other developments in the area around the dike into account during the development and evaluation of the reinforcement.

6.4.2 Part 2: comparative cost-effectiveness

The preceding section compared the discounted lifecycle cost of each flexible strategy to the baseline strategy individually. While the results suggested that enabling managerial flexibility via staging the reinforcement strategy can be advantageous, further analysis is required to compare the economic performance of the two flexible strategies against each other. This section presents the results of such a comparative cost-effectiveness analysis. The percentage of saved lifecycle costs are computed with the use of Equation (4) for every Ssr and Spr strategy.

Acknowledging that sea level rise uncertainty is just one factor among the many uncertain conditions that can affect cost-effectiveness computations, the uncertainty about the discount rate is also explored in this part of the analysis. Accordingly, the computations are conducted for four discount rates of 1%, 3%, 5%, and 7% as well as the two SLR scenarios. For ease of analysis, three case studies are selected among the eight cases of the preceding section. The three cases are representative of the dikes with low level of development (S2), medium level of development (S4) and high level of development (S5).

The results of the comparative analysis are plotted in Figure 24. The graphs on the left side show the results for the low SLR scenario and the graphs on the right side show results for the high SLR scenario. In each column of the graphs, the applied discount rates ascend top-down. In each graph, a bar with a positive value shows that the associated strategy is more cost-effective than the baseline and vice versa for bars with negative values. The higher the absolute value of a positive bar, the higher the relative value of flexibility embedded in that associated strategy is. In contrast, a negative value shows that the baseline has been more cost-effective than that specific strategy.

It can generally be seen that in every graph, independent of the scenario and discount rate, the value of flexibility is higher for the monofunctional dike (S2) compared to the multifunctional dikes (S4 and S5). Because variable costs of reinforcement are much higher for monofunctional dikes, delaying the investment to a later time in the future becomes favourable. This observation is consistent with the observations in the preceding chapter. While it seems to be always advantageous to stage the dike reinforcement for monofunctional dikes, care should be taken in assuming that the staged development of dikes is also a preferred strategy for multifunctional dikes, especially when the ratio of f/v is high.

Comparing the results for different discount rates, the value of embedded managerial flexibility increases as the applied discount rate is higher. This is valid for every Ssr and Spr strategy irrespective of SLR scenario. It should be noted that the computation in this research only addresses the lifecycle costs. Hence, it is advantageous to delay the reinforcement decision since the future costs are discounted. It can be expected that if the benefits of increasing flexibility are also considered, as common in cost-benefit analysis, then delaying the investment decision may not always be advantageous. For example, if a high discount rate applies, benefits in the far future will not count, and hence will be lower than if a low discount rate is applied. Additionally, the present value of such benefit in the future may not compensate the cost of an early reinforcement, in particular for a high discount rate. This indicates that the uncertainty about the discount rate needs to be explicitly addressed in the economic analysis. Therefore, the decision whether to enable managerial flexibility for a reinforcement strategy should not be made by relying on the discounted lifecycle costs.

Generally, the percentage of saved life cycle costs for every strategy and case study is higher for the low SLR scenario (the left side graphs) compared to the high SLR scenario (the right side graphs). This is because the baseline strategy of this research is based on the high SLR scenario. The dependence of the results on the SLR scenario is especially important when the computed percentage is positive in the low SLR scenario and negative in the high SLR scenario. A very clear example of this situation is provided by the computations for Ssr10 in case S4 for the discount rate of 3%. If the decision on the choice of this strategy is made based purely on one SLR scenario, it could be different depending on which scenario is used. Complementary to the conclusion of the preceding section, this indicates that also uncertainty about sea level rise needs to be explicitly addressed. While the two SLR scenarios of this research enable sea level rise uncertainty to be partially addressed, it is acknowledged that the use of only two scenarios is too limited to explore the value of embedding managerial flexibility in a reinforcement strategy. For instance, it can be well expected that flexibility becomes a more valuable attribute when a more extreme SLR scenario than the pessimistic one included here occurs.

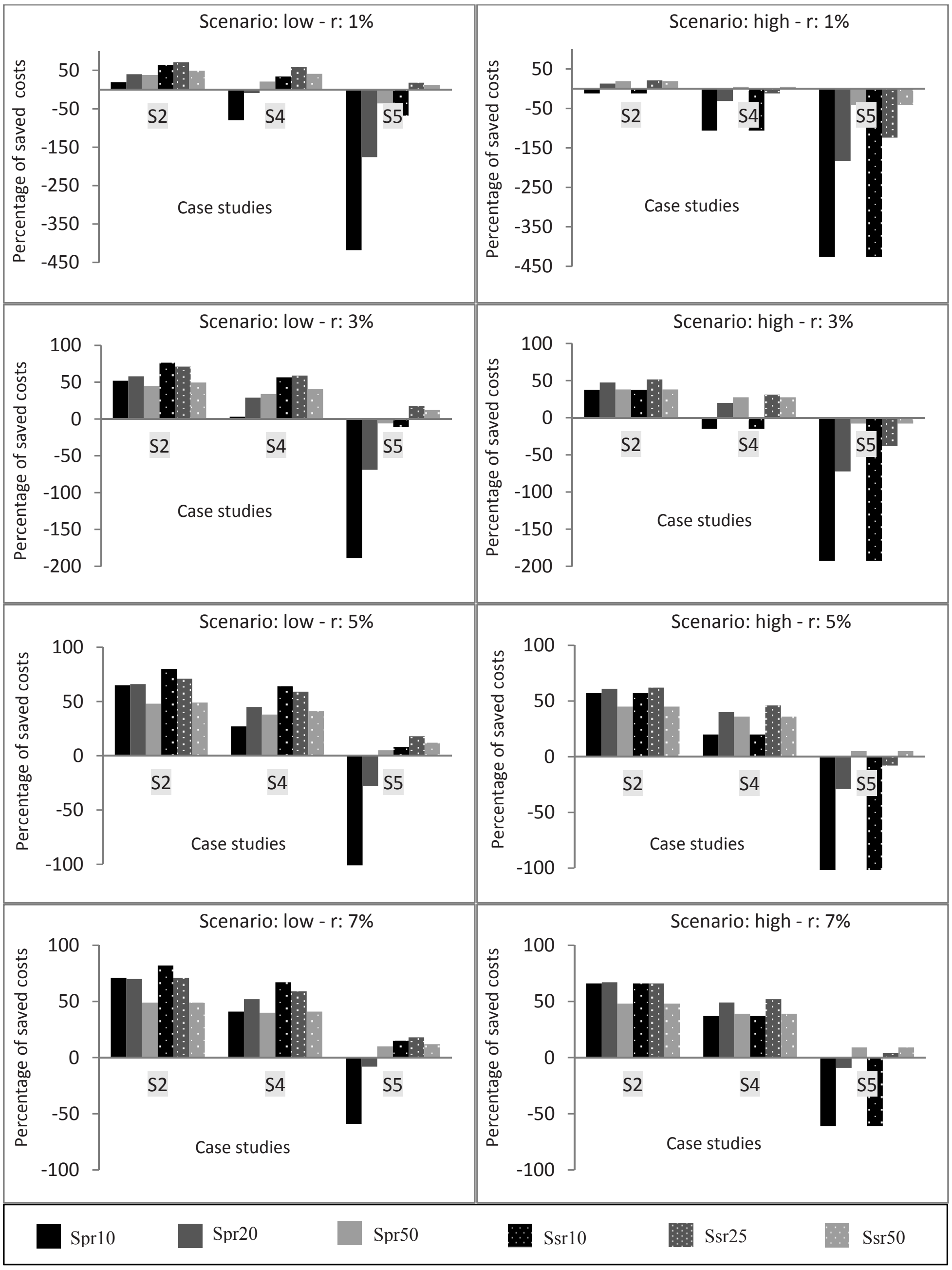

Figure 23, the comparative cost-effectiveness analysis results. The left graphs show the results for the scenario low and right graphs for the scenario high. The discount rate is ascending from the top graph to the bottom graph.

Comparing the percentage of the saved lifecycle costs for each Ssr and Spr strategy, it can be seen that Ssr25 and Ssr50 are the only two strategies that always remain positive in every case study in the low SLR scenario. In high SLR scenario, it is only Ssr50 that remains positive or close to zero in almost all cases. On the other hand, Spr10 and Spr20 show the most negative values, especially for S5 (a highly urbanised area). Roughly, it can be seen that the choice of the 'predict & respond' strategy is more likely to result in less cost-effective discounted lifecycle costs compared to 'sense & respond'. Furthermore, the percentages of the saved lifecycle costs are more positive in the low SLR scenario compared to the high SLR scenario, which highlights the advantageous of not being precautionary.

6.5 Limitations of the study

There are a number of key limitations to the analysis of the present paper, mostly related to the underlying assumptions of the evaluation model. The applied reinforcement cost function in the present paper is based on the best exponential fit to the available data as developed by Kind (2011 and), Eijgenraam et al. (2012) and applied in De Grave and Baarse (2011). The exponential fit was originally developed for the purpose of optimisation of the costs and benefits of flood protection (Den Hertog and Roos, 2009). Besides the exponential fit, there are other types of cost function including the linear cost function (Dantzig, 1956) and quadratic cost function (Eijgenraam et al., 2012), which have also been developed for calculating the reinforcement costs in different studies. It is acknowledged here that the choice of the cost function can alter the computational results of this research. For example, the discounted lifecycle costs computed by a linear cost function can become independent of the sea level rise scenario when the variable cost (v) is nearly zero, as in the case of densely developed urban areas.

This research has focused on evaluating managerial flexibility embedded in reinforcement decision making. The reinforcement costs are used to evaluate flexibility. In reality, implementation of a reinforcement strategy has other socio-economic impacts, such as nuisance and the lag time (the required time to decide on an appropriate action) that are not addressed in this research. Furthermore, while the choice of reinforcement interval of 10 years appears to be cost-effective in some situations, in practice, it is not necessarily a feasible choice to reinforce the dikes every 10 years. Additionally, dike reinforcement in this research in only aimed at preventing overtopping. Hence, the other types of failure mechanisms that may require dike reinforcement are not included. Holistic analysis of a reinforcement strategy should also account for other criteria that may influence the choice of the strategy.

The baseline strategy used in this research appears to be more cost-effective than the flexible strategies, especially in the cases with a very high f/v ratio. It is however very unlikely that a dike would undergo no change in 100 years as assumed in the baseline strategy. For example, the use of only two SLR scenarios in the analysis of this research does not show what will happen if a more extreme SLR occurs. It can well be expected that in such a case the incurred costs of the consequent flood damage would make the baseline an unattractive choice (and that in reality earlier adaptations would be implemented).

A linear trend was selected for the SLR scenarios of this research. It is acknowledged that the selection of a different trend can impact the results. For example, higher sea water levels will happen in the far future when an exponential rather than a linear SLR trend is chosen. Such a choice will be in favour of delaying the reinforcement interventions. In contrast, if sea water levels rise faster, the baseline strategy can be more favourable. Neither this research nor conventional engineering practice addresses the consequences of choosing different sea level rise trends.

The estimations of fixed (f) and variable (v) costs in the database of this research are based on averaged estimates of the unit cost for each dike section. Changing the underlying assumptions of the cost estimate may change the results. Note that, in spite of this expectation, the suggestion of this research regarding the need for consideration of both fixed and variable design lifetimes remains unchanged. Additionally, this research does not address the situation in which the lifespan of the secondary function(s) is shorter than the reinforcement intervals of the dike. For example, the life span of a wind turbine is in the order of 10 years. If the secondary function of the dike comprises wind turbines, the presence of these wind turbines will not impede the reinforcement practice because the turbines will be removed before the next reinforcement practice. The presence or lack of presence of the secondary function(s) at each reinforcement time has not been addressed in this research.

Last but not least, this research has only addressed a precautionary decision maker who chooses the most pessimistic scenario in order not to experience any flood damage. Other types of approach such as risk neutrality have not been considered in the present paper.

Moreover, the potential benefits of reducing flood consequences are also not addressed in the cost-effectiveness analysis of the research.

6.6 Summary and conclusions

The Dutch Government aims to develop strategies that minimise the costs of flood protection over long periods of typically 50-100 years while maintaining sufficient safety and maximising flexibility (Van Alphen, 2015, Kind, 2014). Developing and evaluating such strategies is challenged by various uncertainties. To handle uncertainty about sea level rise, two reinforcement strategies with embedded managerial flexibility are analysed in this paper. The flexible strategy (the 'predict & respond (Spr)') provides the decision maker with managerial flexibility to decide the dike height in predetermined time-steps. The other flexible strategy (the 'sense & respond (Ssr)') gives the decision maker the possibility to reinforce the dike whenever the sea water level rises to a predetermined value, ΔSLR. A cost-effective analysis is conducted, first, to compare each flexible strategy against a baseline strategy and, second, to contrast the two flexible strategies against each other.

The objective of this research is to explore to what extent increasing the flexibility of a reinforcement strategy can result in lifecycle cost-effectiveness, taking into account the other developments around a dike section. To do this, sea level rise uncertainty is addressed in two ways. First, in the specifications of each flexible strategy, four time-steps for the Spr and four ΔSLR thresholds for the Ssr strategies are determined based on the anticipated maximum sea level rise in the two SLR scenarios of this research. Second, the computations are conducted for two SLR scenarios. In addition to sea level rise uncertainty, four discount rates are also used to address this economic uncertainty. The analysis of the research is conducted for eight cases of mono-/multifunctional dikes in the Netherlands.

It was clearly observed that the cost-effectiveness of each flexible strategy varies by the choice of time-steps and ΔSLR thresholds. Roughly, a medium value chosen for the design lifetime/ ΔSLR threshold seems to be more advantageous for monofunctional dikes. On the other hand, a higher value chosen for the design lifetime/ ΔSLR threshold seems to be more advantageous for multifunctional dikes. Considering the two SLR scenarios, it is indeed not possible to conclude one set of design lifetime/ ΔSLR thresholds is the most advantageous choice. However, it is very clear that determining the timing of reinforcement based on only one SLR scenario, as is common in conventional engineering practice, needs to be improved.

Besides these conclusions, it was also observed that the 'predict & respond (Spr)' strategy is more likely to result in less cost-effectiveness results compared to the 'sense & respond (Ssr)' strategy. This result indicates that reinforcing the dike in variable time-steps (or choosing a variable design lifetime) can result in more lifecycle cost-effectiveness compared to reinforcing the dike in pre-determined time steps (or choosing fixed design lifetimes). This observation is especially true when the low SLR scenario occurs. While the use of only eight case studies is not sufficient to generalise this conclusion, it is strongly recommended that conventional engineering practice can potentially be improved by taking into account the reinforcement strategies with variable design lifetimes as well.

Regardless of the chosen time-steps and ΔSLR thresholds, the Spr and Ssr strategies appear to be cost-effective in every case study of monofunctional dikes. The monofunctional dikes of this research have significantly higher variable costs compared to the multifunctional dikes. For this reason, delaying the reinforcement decision to a later time and using a higher discount rate lower their lifecycle costs. As a consequence, the value of embedded managerial flexibility is then partly due to the impact of discounting. This conclusion does not necessarily hold for multifunctional dikes. This indicates that cost-effectiveness of a reinforcement strategy is heavily dependent on the situational specific characteristics of the case studies. Furthermore, since the choice of applied discount rate crucially impacts the computed lifecycle costs and the comparative cost-effectiveness, it is strongly recommended the valuation of flexibility should not be solely based on economic analysis. This is especially important for the cases with higher f/v ratios when a strategy seems to be cost-effective for a high discount rate, but not to be cost-effective for the lower discount rates.

Flexibility is also advantageous due the enabled possibility to adjust the reinforcement decision recurrently. Having the possibility to adjust the reinforcement strategy based on the observation of sea level rise can prevent overinvestment if a lower sea level happens and mitigate underinvestment if a higher rise sea level happens. Hence, the embedded managerial flexibility in either the Spr or Ssr strategy has the potential to provide significant benefits to long term flood protection.

The SLR scenarios used in this research are based only on a linear trend of sea level rise and they do not address the possibility of different rates of sea level rise. The corresponding uncertainty can be addressed more explicitly when many different scenarios of sea level rise are used. Further research is needed to explore how the value of flexibility, to handle uncertainty, can be potentially impacted by the choice of sea level rise trend and the combination of scenarios.

In the present paper, it is assumed that reinforcement practices should not influence other structures in the area around dikes. Hence, more sophisticated reinforcement measures are often required for multifunctional dikes. In fact, flexibility can embedded in the design of the secondary function(s) in order to accommodate the ease of reinforcement. An example of such design flexibility is the case of movable buildings located on top of a dike in some parts of the Netherlands. If the dike needs to be reinforced, the platforms (underneath the whole of the buildings) can be easily raised, which makes space for the dike to be reinforced. The initial cost of such movable structures might be higher, but may be just a small fraction of the whole construction costs. Consequently, the lifecycle cost of reinforcement and raising the buildings might be lower. This research does not address how the design flexibility embedded in the secondary function can impact the lifecycle cost-effectiveness. In accordance with the discussions in Section 4, the lifespan of the secondary function needs to be addressed in the economic analysis as well. Overall, it is strongly recommended that reinforcement decision making needs to account for smaller scale developments in the area around dikes. Future research is necessary to investigate the many different ways in which flexibility can be embedded in the design and management of multifunctional flood defences. Better evaluation models are also needed to enable investigating different types of benefits associated with those strategies. The Dutch Government aims to develop strategies that minimise the costs of flood protection over long periods of typically 50-100 years while maintaining sufficient safety and maximising flexibility (Van Alphen, 2015, Kind, 2014). Developing and evaluating such strategies is challenged by various uncertainties. To handle uncertainty about sea level rise, two reinforcement strategies with embedded managerial flexibility are analysed in this paper. The flexible strategy (the 'predict & respond (Spr)') provides the decision maker with managerial flexibility to decide the dike height in predetermined time-steps. The other flexible strategy (the 'sense & respond (Ssr)') gives the decision maker the possibility to reinforce the dike whenever the sea level rises to a predetermined value, ΔSLR. A cost-effective analysis is conducted, first, to compare each flexible strategy against a baseline strategy and, second, to contrast the two flexible strategies against each other.

The objective of this research is to explore to what extent increasing the flexibility of a reinforcement strategy can result in lifecycle cost-effectiveness, taking into account other developments around a dike section. To do this, sea level rise uncertainty is addressed in two ways. First, in the specifications of each flexible strategy, four different time-steps for the Spr and four different ΔSLR thresholds for the Ssr strategies are chosen for analysis, based on the anticipated maximum sea level rise in each of the two SLR scenarios taken into account in this research. Second, the computations are conducted for two SLR scenarios. In addition to sea level rise uncertainty, four discount rates are also used to address this economic uncertainty. The analysis of the research is conducted for eight cases of mono-/multifunctional dikes in the Netherlands.

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7 Conclusions & discussions

"Men are born soft and supple; dead, they are stiff and hard.
Plants are born tender and pliant; dead, they are brittle and dry.
Thus whoever is stiff and inflexible is a disciple of death.
Whoever is soft and yielding is a disciple of life. The hard and
stiff will be broken. The soft and supple will prevail."
Lao-tzu, 6th century B.C. Chinese philosopher, founder of Taoism

7.1 Overview of the research completed

This dissertation started by discussing that it might be possible to make use of the struggle against rising sea levels in coastal areas as an opportunity to boost societal and economic growth. As suggested in the literature, multifunctional use of flood defences is proposed as a promising way of increasing the synergy between flood protection and urban development as well as to improve the cost-effectiveness of flood protection strategies. A multifunctional flood defence, in this research, represents a system of a flood defence (mainly a dike) and one or more (non-water retaining) secondary function(s) located around/ on top /inside it. The secondary functions must be partially or fully located in the flood protection zone of the flood defence.

It was discussed that the design and management of multifunctional flood defences is a complicated and challenging task. Such infrastructure is expected to maintain its desired performance throughout its lifetime. The (physical, technical, political) environment of the system as well as the system itself evolves dynamically and steadily. Therefore, it is likely that the desired performance of the system in the future will be different from what is expected now. Successful design and management of multifunctional flood defences in a dynamic contemporary environment need not only to address today's needs but also to accommodate tomorrow's uncertain requirements. Accordingly, the research presented in this dissertation has revolved around the issue of design and management of multifunctional flood defences under uncertainty. In the presence of uncertainty about future change, the main challenge addressed in this research is how to enhance the capability of a multifunctional flood defence to enable its desired performance to be maintained under changing conditions.

To better understand the dynamics governing significant changes in the past, a case study of the evolution of multifunctional flood defences in Vlaardingen, Vlissingen, Afsluitdijk and Brouwersdam is presented in Chapter 2. It is seen that the use of land has gradually evolved to become a multifunctional flood defence. It is observed that various drivers of change have emerged, evolved, interacted, and aggregated in complex and non-linear ways and have resulted in the current multifunctional flood defences. Moreover, the presence and lack of flexibility in the design of multifunctional flood defences is found to be a critical factor in shaping the future of the system. It is concluded that the future cannot be predicted based on a simple extrapolation of the past. Therefore, there is a need to find the design and management strategies that would be better at coping with the complex internal and external changes that can frequently move a multifunctional flood defence out of the domain it was conceived for.

A review of literature on handling uncertainty and change has been undertaken in Chapter 3. It is found that resilience, robustness and flexibility are the three system attributes proposed to handle future uncertainties. The term 'robustness' is used in two ways to refer to a system capability to resist change (system robustness), and also to present a performance criterion to select between different strategies developed to handle uncertainty (e.g. in robust decision making). While the three attributes seem to be different in definition, they are not mutually exclusive in practice. Moreover, it is also observed that flexibility is the least rigorously explored concept among the three system attributes for handling uncertainty. It is concluded in this chapter that the discussion about any of these attributes should start by clarifying the addressed concept(s).

Taking into account the potential advantages of considering flexibility, the main objective of the research presented in this dissertation is to systematically explore different aspects related to incorporating flexibility in the design and management of multifunctional flood defences. Based on the insights gained from the case studies of Chapter 2 and literature review of Chapter 3, it is proposed that the proper treatment of flexibility requires supplementary approaches that can help designers and decision makers to identify the options for increasing flexibility and to evaluate them in the context of multifunctional flood defences. Accordingly, three specific objectives are defined to address some of these issues in this research. The research conducted to address these objectives is summarized in the following.

7.1.1 Objective 1: conceptualising flexibility

The literature review of Chapter 3 demonstrates that despite the interest of the scientific community in considering flexibility, it is still a vague concept in flood risk management. This observed ambiguity about the concept of flexibility prompted the first objective of the research. Accordingly, the first question of the research was framed as:

1) What is flexibility and how to characterise and define it in the context of multifunctional flood defences?

An extensive literature review is carried out to develop a framework for conceptualising flexibility in Chapter 4. Reviews of publications on flood management, real options and manufacturing reveal remarkable commonalities along with substantial inconsistencies in the interpretation and use of flexibility in each domain. The presence of inconsistencies and contextual differences in different domains does not allow for adopting the concept of flexibility from a specific field. The commonalities in interpreting and characterising the concept of flexibility in different domains are used in this research to develop a framework for conceptualising flexibility in the context of multifunctional flood defences.

The proposed framework in this research takes the form of four self-consistent and step-wise questions. Eight characteristics features are distilled from the synthesized publications in order to guide answering these four questions clearly and consistently. The names of the characteristics features associated with the four questions of the framework are bolded and underlined below.

(Q1) Why is flexibility needed?

- This question establishes the motivation for consideration of flexibility. This can be done by identifying the type of **change** (internal or external to the system) and **uncertainty** (e.g. sources, levels) that is chosen to be handled.

(Q2) What is it that flexibility is required for?

- This question seeks to describe the competences of flexibility to be specified as the **goal** of flexibility consideration (to handle the downsides or upsides of uncertainty) and the **capabilities** of flexibility to achieve its goal (via time, performance, cost penalties prevented).

(Q3) What are the dimensions of flexibility?

- This question indicates the extent to which flexibility can be achieved, from a **temporal** point of view (strategic/tactical/operational) and the **mode of response** (proactive/reactive).

(Q4) What needs to change or be adapted?

- This question discusses the potential ways of achieving flexibility. In this research, flexibility **types** (or managerial flexibility) indicate the managerial actions and decisions that should be taken to consider and use flexibility while flexibility **enablers** (or design flexibility) refer to the sources of flexibility (or where flexibility is) embedded in the system's technical design.

Subsequently, the following working definition of flexibility is developed as:

'*a multifunctional flood defence system's attribute that enables responding to changing conditions, in order to reduce the negative consequences, and/or to exploit the positive upsides of uncertainty and change, in a performance-efficient, timely and cost-effective way*.'

To demonstrate the potential of this framework, it is applied to the conceptual design of a multifunctional flood defence. The context for the case study application is taken from an existing multifunctional flood defence in the Netherlands, in which a series of residential and commercial buildings have been built on top of a sea dike. First, the framework is applied to the discussion of flexibility options for the dike and the buildings separately. Afterwards, the framework is applied to the combined structure including the buildings constructed on top of the dike. It is observed that the multifunctional use of flood defences connects the (physical, technical, political and institutional) environment of the functional components of the system. Therefore holistic flexibility consideration for multifunctional flood defences cannot be achieved by simple superposition of flexibility for each system component.

It is argued that the iterative use of the framework can assist the process of identifying the sources of flexibility in the design and management of multifunctional flood defences.

Depending on how the four questions of the framework (Q1-Q4) are answered, it will become possible to identify different ways of increasing flexibility in the design and management of multifunctional flood defences. Moreover, when there is more than one possibility for increasing the flexibility of a multifunctional flood defence, trade-offs can occur between the different options for flexibility. Quantifying the capabilities of flexibility (performance, time, cost loss preventions) associated with each option can be used to assess the value of embedded flexibility as well as to rank the options.

For example, if flexibility is aimed at handling sea level rise in a cost-effective way; the extent of cost-effectiveness achieved by an option for flexibility can be used to evaluate this embedded flexibility. In another example, it can be expected that when a multifunctional flood defence needs adjustment to changing conditions, there might be more than one possible path that can be taken at that time in response to change. If the possibility of taking different paths has been considered as a way of increasing the flexibility of a multifunctional flood defence system in the initial design, the number of possible paths that can be taken at each stage can be used to rank the different options for flexibility. Roughly speaking, the option that provides a wider range of possible paths to be taken at future decision points can be considered as a more flexible option compared to the other options with a smaller range of manoeuvrability.

Overall, it is concluded in Chapter 4 that the step-by-step use of the proposed framework can guide and structure the discussion of flexibility for multifunctional flood defences. Moreover, the use of the eight characteristic features associated with the four questions of the framework can reduce confusion about the concept of flexibility by providing a unified set of terminologies that are clearly defined. It can therefore be claimed that proposed framework has to the potential to reduce the vagueness over the concept of flexibility and, in turn, to increase the clarity about the concept of flexibility in the context of multifunctional flood defences.

7.1.2 Objective 2: functional modelling and performance analysis

Reliability analysis methods are commonly applied to assess the performance of the flood defence. While it is very difficult to precisely assess the performance of a flood defence with the current reliability analysis methods, the situation becomes far more complex for multifunctional flood defences. Multifunctional use of flood defences is expected not only to link the performances of the functional components of the system, but also to connect the (physical, technical, political) environments of these combined functions. Therefore, it is concluded in Chapter 4 that holistic flexibility consideration for multifunctional flood defences need to address these complex interactions.

The need for an approach for a more complete performance analysis of multifunctional flood defences prompted the second objective of this research. Accordingly, the second research question is:

2) How to model the functional performance of a multifunctional flood defence in order to be used to devise strategies for maintaining the desired performance of the system under uncertainty?

To answer this question, a multifunctional flood defence is defined as '*a zone that is primarily used for flood protection, but serves other non-water-retaining functions (e.g. transportation, housing).'* In this research, dependencies refer to both the *intended* links between the functional components of a multifunctional flood defence as well as the *potential* dependencies between these functional components that can emerge under changing conditions. The intended dependencies between the functions of a multifunctional flood defence are addressed via the use of the two groups of physical and geographical dependencies. *Physical dependency* implies a link between the functions in such a way that the performance of one function becomes a requirement for another function to perform its desired task. *Geographical dependency* occurs where the structural components of a multifunctional flood defence are co-located in such a way that a local environmental event can affect all the components.

The Functional Resonance Analysis Method (FRAM) is adopted and customised for prospective performance analysis (or risk analysis) of multifunctional flood defences. The risk analysis process (in Chapter 5) focuses on identifying the positive and negative outcomes of potential dependencies caused by changes in the performance of the functional components of multifunctional flood defences. It is a qualitative approach in which the term 'risk' is applied to refer solely to the positive and negative outcomes of potential dependencies without discussing and assessing the probability of occurrence. The positive and negative outcomes refer to the unexpected favourable and unfavourable changes in the performance of a target function.

The customised method proposed in this research consists of five steps for breaking apart a multifunctional flood defence into the functional components that are relatively well known, identifying the intended and potential dependencies between these functions, and investigating the scenario based impacts of the potential dependencies on a target function. The functional components of a multifunctional flood defence are characterised by six aspects, namely the: 'time', 'control', 'precondition', 'resource', 'input', and 'output' (further explained in Chapter 5). The description of the functional components and their functional aspects is then used to investigate the potential dependencies caused during a scenario-specified event. The scenario under consideration should, at least, address variability in the normal performance of the functional components of the system.

The customised methodology is applied to compare four alternative designs of a multifunctional food defence in a scenario of an extreme event. The contexts of the four alternatives are taken from two design alternatives developed for the multifunctional flood defence at Katwijk. The alternatives are developed to represent different levels of intended physical and geographical dependencies. The functional model of each example is developed and used to explore the impacts of the secondary functions on the flood protection function, which is the target function under consideration. For each of the four alternative designs, graphical representations of the functions were used to illustrate the identified potential dependencies and their (positive/negative) impacts.

It is seen that constructing a parking garage within a short distance of the dike is not necessarily safer than constructing a parking garage in the body of the dike. Moreover, it is observed that, in addition to the technical performance of the system, human actions related to the secondary function of the system can have an important role in weakening or strengthening the flood protection function. Additionally, it is observed that increasing the physical and geographical dependencies can increase the number of potential dependencies, but not necessarily the number of negative impacts on the target function.

It is argued the identified negative impacts can act as a signal that something needs to be done in order to prevent the undesirable potential dependencies from being created or to mitigate the negative impacts of these dependencies. In contrast, the positive impacts of potential dependencies indicate ways of improving the performance of the flood protection function that should be highlighted and enabled in the design process. Furthermore, it is briefly discussed that improving the capability to better address the (positive/negative) impacts of potential dependencies, in the technical design of multifunctional flood defences, will increase the flexibility required to handle unwanted disturbances. Additionally, it is suggested that the number of identified potential dependencies and their impact types (positive, negative) can provide additional information to be used for determining the better performing alternative designs of a multifunctional flood defence.

Overall, it is concluded in Chapter 5 that the customised performance analysis method of this research appears to be a promising method capable of modelling the functional components of multifunctional flood defences and their dependencies. This method is found to be useful for describing and visualising the interactions between the human actions, technical components, and the environment of the system. The analysis results can support the design of a multifunctional flood defence that enhances its capability to maintain its desired performance under changing conditions.

7.1.3 Objective 3: valuing flexibility

Flexibility is generally perceived as an advantageous system capability in Chapters 4 & 5. It was, however, stated in Chapter 4 that if flexibility is aimed at enabling a cost-effective response to changing conditions, the extent of its effectiveness needs to be evaluated.

The case studies of Chapters 4 & 5 demonstrate that flexibility is a multidimensional concept which can be achieved in many different ways. In flood risk management literature, managerial flexibility is often addressed and assessed as a way of handling climate change uncertainty. Managerial flexibility is enabled by giving decision makers the option to revise their decisions in accordance with the arrival of new information in several reinforcement stages.

In the context of multifunctional flood defences, the presence of secondary function(s) can impede the use of normal dike widening/heightening to reinforce the dike. Therefore, it needs to be examined whether increasing managerial flexibility via enabling dike reinforcement in several stages will be advantageous for multifunctional flood defences. The need for such an assessment led to the third objective of this research. It was proposed to achieve this objective by formulating the third research question as:

3) To what extent does an increase of the managerial flexibility improve the lifecycle cost-effectiveness of reinforcement of multifunctional flood defences?

The third question of the research is addressed in Chapter 6, where managerial flexibility is embedded in reinforcement decision making by enabling staged reinforcement of dikes. Flexibility manifests itself in the determination of the reinforcement intervals (or design lifetime/ time-steps). This managerial flexibility is taken into account as an enabler of timely and cost-effective response to uncertain changes in sea level rise.

Two reinforcement strategies with different principles toward determining the reinforcement intervals are developed and compared to a baseline strategy. The 'predict and respond (Spr)' is a flexible strategy in which dike reinforcement decisions are made (and implemented) in predetermined time-steps. This means that the design lifetime of such a reinforcement strategy (or the reinforcement intervals) is fixed in time. This strategy is very similar to the current practice of dike reinforcement in the Netherlands. The 'sense and respond (Ssr)' is a flexible strategy in which the time steps of reinforcement (the design lifetime) are determined based on the evolution of sea level rise. In the latter strategy, the dike can be reinforced at any time. The two strategies are compared to a baseline strategy in which the decision for the reinforcement is fully specified and implemented in the first year of a 100 year analysis period.

The reinforcement costs of strategies are calculated with the use of an exponential cost function that has already been applied in several studies for finding optimal dike heightening strategies in the Netherlands. Due to the uncertainty about the extent of sea level rise and its impact on coastal flooding, projections of sea level rise are used for both development and evaluation of the two flexible strategies. In developing the strategies, sea level rise uncertainty is addressed by assigning different design lifetimes/ΔSLR thresholds to each flexible Spr and Ssr strategy. Additionally, in order to address the uncertainty about the discount rate, the cost-effectiveness analysis is also examined for four discount rates.

Empirical data from eight cases of mono- and multifunctional flood defences in the Netherlands are used to assess and compare the cost-effectiveness of the developed strategies. The chosen case studies are grouped into three levels of development based on the ratio of fixed over variable costs (f/v). For each group, one type of reinforcement is addressed based on the availability of space between the dike and its secondary function(s).

It is assumed that the dike section under study has to maintain sufficient safety in the time interval between the two reinforcement practices. The benefits associated with providing extra safety, or the costs resulting from a lack of a certain amount of safety have therefore not taken into account. The analysis is conducted in two parts. First, the discounted lifecycle costs of each flexible strategy are compared to the baseline strategy. The assessment is conducted for all the eight case studies and with the use of a single discount rate. Second, the lifecycle costs of the two flexible strategies are compared to each other for three representative cases (among the eight cases) and for four different discount rates.

It is observed that the lifecycle costs of all the flexible strategies are always lower than the lifecycle costs of the baseline strategy for the monofunctional dikes (with low f/v ratio). This observation confirms the results of previous studies carried out for monofunctional flood defences in different countries, such as Bangladesh and Tanzania (Linquiti and Vonortas, 2012), in UK (Woodward et al., 2011) and Mexico (Scandizzo, 2011). The results for highly urbanised areas (with a very high f/v ratio) do not show any distinct advantage in favour of increasing the managerial flexibility of the reinforcement strategy, in particular if the high scenario of sea level rise is examined. Additionally, it is observed that shorter design lifetimes (for Spr strategies) and/or ΔSLR threshold (for Ssr strategies) seem to be more cost-effective for the mono-functional dikes, while higher design lifetimes/ ΔSLR threshold seem to be slightly more cost-effective for the multifunctional dikes. It is therefore concluded that it is of utmost importance to take the other developments in the area around the dike into account during the development and evaluation of a reinforcement strategy. The dependency of cost-effectiveness on the choice of SLR scenario clearly indicates that determining the reinforcement intervals with the use of only one scenario may not result in achieving the desired cost-effectiveness if sea water levels rise differently than expected.

The baseline strategy of this research is based on the prediction (but not anticipation) of sea level rise for 100 years. The lifecycle cost of the baseline strategy might thereby be overestimated. It is, however, seen that in the cases with higher f/v ratios, the baseline strategy can even be cheaper than the Spr and Ssr strategies. Overall, it is observed that the choice of 'predict & respond' strategy is more likely to result in less cost-effective discounted lifecycle costs compared to 'sense & respond'. Hence, it is concluded that it can be inappropriate to choose the staged reinforcement as the preferred strategy for every dike section, especially when the ratio of f/v is high.

Comparing the results for different discount rates, the value of embedded managerial flexibility (in both the Spr and Ssr strategies) increases as the applied discount rate is higher, irrespective of the SLR scenario. The choice of the discount rate appears to significantly influence the extent of the cost-effectiveness. The results also seem to be very sensitive to the fixed costs, perhaps even more than the choice of discount rate. It is therefore argued that the uncertainty about the discount rate needs to be explicitly addressed in the economic analysis.

It is admitted that the use of only eight case studies is not sufficient to generalize the results of this research. Despite the limitations of the analysis, it can still be expected that by increasing the design flexibility of a multifunctional flood defence in initial design phase, the value of increasing managerial flexibility in reinforcement planning increases and the lifecycle costs can be reduced. It is however acknowledged that increasing flexibility comes at a cost which should also be addressed in the evaluation process.

Furthermore, the cost-effectiveness analysis of this research, and many other similar researches, is only carried out for a presumed (linear) trend of sea level rise. In reality, if projections of sea level rise changes in time, the associated design lifetime will not achieve the specified goal of minimizing the lifecycle costs. To better tackle this issue, the use of a varying design lifetime is suggested instead of a fixed value.

7.2 Discussions

In this section some limitations of the research are discussed first. Then, insights gained during the research are used to discuss the applicability of the concept of flexibility. Finally, the section ends by presenting the implications of the research to the practice of design and management of multifunctional flood defences

7.2.1 Research limitations

The research reported in this dissertation does not offer a complete solution to the problem of design and management of multifunctional flood defences under uncertainty as there are different ways of responding to uncertainty. The choice was made to focus on flexibility mainly because the topic of flexibility and its potentials has not been discussed in the flood risk management literature as much as other concepts such as resilience and system robustness.

Throughout the dissertation, the information about the case studies is limited to what can be inferred from relevant articles and published literature, and to some extent is based on expert opinion. In almost every case study, the collected information was not sufficient to make a firm conclusion about the question under investigation. For example, the investigated historical documents (in Chapter 2) could not explicitly specify whether the decision makers of the past did or did not have any intention to embed flexibility in the design of the flood defences. In another example, the details about the design alternatives for the case of Katwijk were not available to the researcher which limited the depth of the performance analysis presented in Chapter 5.

Furthermore, due to limitations in the state-of-the art knowledge and due to the time and resource limitations of the research, various assumptions were made in order to make the work manageable. For example, due to limitations in the current models, the evaluation process of Chapter 6 assumes that every developed strategy will maintain the minimum level of safety required. Therefore, the benefits of providing extra safety were not taken into account. Furthermore, the scenarios developed and applied in Chapters 5 & 6 were limited to a few extreme situations which are not sufficient to address the wide spectrum of the plausible future possibilities that can occur.

Additionally, although the evolution of multifunctional flood defences in the past has clearly demonstrated that human action and human preferences have had a very, if not the most important, role in shaping the future, the uncertainty about human actions (Chapters 5 & 6) was addressed in this research to a very limited extent. Moreover, among the many uncertain factors that can influence reinforcement decision making, only sea level rise and discount rate uncertainties were addressed in Chapter 6. The main focus of this research has been on uncertainty due to climate change as manifested in sea level rise (Chapter 6).

Finally, the cost function applied in Chapter 6 has been adopted from the literature on economic optimization of flood defences in the Netherlands. Scholars from different countries, however, have developed and applied different evaluation methods, built upon different underlying assumptions. While the purpose of this research was not to provide a definite conclusion on the choice of reinforcement strategy, it can be expected that by using a different method, the results could be different.

7.2.2 Applicability of flexibility

This research starts by addressing flexibility as an advantageous system capability to handle uncertainty and change. With this line of thinking, a roadmap for comprehensive discussion of flexibility in the context of multifunctional flood defences is proposed in Chapter 4 and a method for functional modelling of multifunctional flood defences is presented in Chapter 5. Despite the proposed advantages of flexibility in these two chapters, the evaluation of flexibility in Chapter 6 demonstrates that the value of flexibility is very much dependent on the context of a multifunctional flood defence. Besides that, flexibility is applied in this research to handle some anticipated future changes. There is, however, no guarantee that this flexibility becomes useful if the future unfolds differently than anticipated.

Additionally, flexibility in the design and management of multifunctional flood defences appears as a double-edged sword. While increasing the flexibility of one function can enable the ease of adaptation for it, enabling this flexibility may reduce the flexibility of the other function of the system. For example, as currently practiced in the Netherlands, the flood protection zone of a dike is reserved for future reinforcement of the dike. If a secondary function is placed in this zone, the design and management of it has to accommodate the embedded flexibility in the flood protection zone, which in turn limits the flexibility in the design and management of the secondary function of the system.

In contrast to the previous point, the presence of a secondary structure in the flood protection zone can in some cases increase the flexibility in the design and management of the flood defence. For example, if a series of buildings on top of a flood defence are constructed in such way that they can positively contribute to flood protection, then the presence of a secondary function actually has increased the flexibility in flood protection by enabling a further delay in flood defence reinforcement. An example of this is the flexible buildings on top of the sea dike in Vlissingen. Therefore, the usefulness of any option for increasing the flexibility of multifunctional flood defences will be very much dependent on the intended dependencies between the functions of a multifunctional flood defence.

Furthermore, as clearly stated by authors in the field of manufacturing, the ‘flexibilization’ (Pollert, 1988) should not become an ideology undermining the need for rigidity (Gertler, 1988). It is believed that there is a trade-off between flexibility and efficiency in responding to change whereby increasing the flexibility is expected to reduce the efficiency of a system (Olsson, 2004). For example, increasing the flexibility by delaying reinforcement investment decisions to a later time may also delay the provision of timely and sufficient safety.

The future of multifunctional flood defences can develop in multiple ways. Flexibility considerations are associated with our current knowledge and are oriented towards supporting stability and providing a continuous and reliable service. There is a puzzle here. When flexibility is used in an anticipatory way to handle the needs of the distant future, its benefit is expected be materialised far into the future. In order to evaluate this benefit a long analysis period needs to be taken into account. On the other hand, by taking into account the possibility of experiencing a very different future, it can be expected that the underlying assumptions and the results of such an analysis can be significantly in error. This makes it difficult to evaluate flexibility and rank the options since it is not easy to develop and select proper time-independent criteria that address both the needs of today and tomorrow.

Finally, given the fact that multiple drivers of change at different spatial and time scales interact and that it is not possible to predict the future of a multifunctional flood defence, it can be concluded that considering flexibility for addressing just a few sources of uncertainty may not be effective in addressing the needs of the future. Added to that, observing the role of human action on land use change over time demonstrates that, perhaps focusing on increasing the human dimensions of flexibility can be more effective than focusing on the flexibility of technical design. This indicates that, for instance, increasing managerial flexibility with the goal of improving agility in the decision making process can be always useful for enabling a faster reaction to change.

7.2.3 Implications of the research

Despite the limitations of the research and the concept of flexibility itself, the research results can still have important implications for the decision makers of multifunctional flood defences:

1) It was concluded in Chapters 2 & 3 that shaping development decisions based on the past data and trend prediction is likely to fail in addressing future needs. This indicates that adaptation planning needs to pay special attention to the surprises that may happen in the future. This can be achieved by improving the capability to react properly to unexpected circumstances.

2) It was shown in Chapter 4 that considering flexibility for a multifunctional structure cannot be properly done in isolation. As also concluded in Chapter 5, addressing the uncertain impacts of various interactions caused by multifunctional use of flood defences should become an integral part of handling uncertainty and the consideration of flexibility.

3) As discussed in Chapters 4 & 5, in order for the design and management of a multifunctional flood defence to be well prepared to respond to changing conditions in the future, the designers and managers of one function need to have a clear understanding of the requirements of the other function(s). The use of a unified set of terminology as provided in Chapter 4 & 5 can facilitate mutual understanding and prevent miscommunications.

4) The cost-effectiveness analysis of Chapter 6 demonstrates that using a variable design lifetime, which is not common in current engineering practice, can potentially reduce the lifecycle costs of reinforcement. Furthermore, smaller scale developments in the flood protection zone at the sides of a dike should be included in the economic appraisal of flood defences.

5) Comprehensive treatment of flexibility requires tools and methods for identifying and evaluating flexibility. While the conceptual framework of Chapter 4 proposes the generic steps required for identifying and evaluating flexibility for multifunctional flood defences; The performance analysis of Chapter 5 complements the steps 1 and 4 of the framework of Chapter 4. This is because the scenario based anticipated changes and their dependencies help in determining the threats and opportunities to be addressed in step 1 of the framework of Chapter 4. The identified positive and negative impacts of the dependencies can then support the process of identifying the sources of flexibility. On the other hand, the cost-effectiveness analysis presented in chapter 6 is focused on evaluation of flexibility. Therefore, the three main chapters of 4, 5 & 6 fill in some of the gaps in addressing flexibility for multifunctional flood defences partially in a systematic and complementary way.

7.3 Main conclusion

The main conclusion of research is that increasing flexibility in the design and management of multifunctional flood defence can indeed be useful to accommodate future changes more effectively. This is mainly because of the enabled possibility of constant learning as well as the possibility to adjust the course of action. Furthermore, flexibility can be aimed at not only handling the negative downsides of uncertainty, but also taking advantage of future opportunities. Therefore, the use of flexibility can also result in more efficient use of the available resources.

It is acknowledged that the extent of change required for addressing future needs will be unknown for now. The presence of surprises and complex interactions among a wider, even global, dynamics supports the statement of Dilling et al. (2015) that adapting to the changes we know now, may introduce new sources of rigidity (inflexibility) as well as new sources of flexibility into the system in the future. This indicates that while future conditions may prevent utilization of embedded flexibility for various (social, political or organizational) reasons, the embedded flexibility in the design and management of multifunctional flood defences may also introduce new ways of handling the needs of future. In presence of uncertainty, this conclusion can be extended to any other system attribute, which is aimed at adapting to future changes, such as resilience and robustness.

Furthermore, it is concluded that the multifunctional use of flood defences does not necessarily reduce the level of safety provided by the defences. Rather, a tight link between the functions of a multifunctional flood defence can, in some cases, improve the performance of the flood protection function. Moreover, the secondary function of a multifunctional flood defence can be designed in such a way to contribute to increasing flexibility in the design and management of the flood defence. Although the initial cost of constructing such secondary functions might be higher, the need for a lower dike and the reduced cost of future reinforcement can arguably compensate this extra initial cost.

It is strongly suggested that, taking into account the lack of knowledge about the many drivers of change and their impacts on the system in the future, care should be taken in the use of a decision making criterion such as cost-minimization, estimated over a long period of analysis.

8 Recommendations & reflections

‘… If I lived twenty more years and was able to work, how I should have to modify the "Origin," and how much the views on all points will have to be modified! Well, it is a beginning, and that is something...’

Charles Darwin in a letter to his friend J. Hooker in 1869

8.1 Recommendations

Flexibility in the design of multifunctional flood defences is still a relatively new topic. Many questions about the flexibility of multifunctional flood defences need to be addressed. Out of the many questions that arose from this research, the following research needs have been selected for discussion here.

1) Need to account for various sources of uncertainty

The main challenge of this research is to handle uncertainty and change in the design and management of multifunctional flood defences. To approach this issue, the flexibility considerations in the case studies of this research are mainly focused on handling uncertainty about sea level rise. A brief consideration of the uncertainty about human, technical and environmental interactions is made in Chapter 5, and about discount rates in Chapter 6.

As discussed in Chapters 2 & 4, it is actually a combination of various socio- economic and natural environmental changes that have influenced the evolution of multifunctional flood defences in the past. Hence, improving the system capability to handle the changes of an unexpected future cannot be properly done by focusing on handling only a few sources of uncertainty. Although it may seem easy to identify many uncertainties relevant to the development of multifunctional flood defences, it is not at all easy to generate feasible options for flexibility that can address these many uncertainties.

In an attempt to identify the sources of flexibility when several uncertainties are addressed, Hu and Poh (2011) have developed a screening method. In this method, the most important sources of flexibility in the system design are determined based on the study of propagation of external changes within the system under consideration. Propagation of change represents the internal interactions that have been instigated by an external change. The intention of this method is to identify the system components that are sensitive to these external changes directly or indirectly. These components are ranked based on the type and number of uncertainties that can impact them. The most sensitive system components are then selected to be become more flexible in such a way to improve their capability to handle several sources of uncertainty. Such a screening method can be further improved and customized for identifying the sources of flexibility for multifunctional flood defences when several uncertainties are taken into account.

The application of such a screening method will require an approach to study the potential dependencies caused by an external change in the environment of the system. It is briefly discussed in Chapter 5 that the customized method of this research has the potential to support identifying the (positive/negative) impacts of potential dependencies caused by the multifunctional use of flood defences. This method can be further improved to identify the functional component that might be the most sensitive to the externally instigated changes. By increasing the capability of the identified components to accommodate future changes, the overall flexibility of the system to handle various sources of uncertainty increases.

2) Need for addressing human cognition

The case study of Chapter 2 shows that human actions (internal or external to the system) have had an even more influential role than the natural environment in the reformation of land use in the past century. Additionally, it is shown in Chapter 5 that human actions and decisions (internal to the system) can significantly impact the desired performance of a multifunctional flood defence both positively and negatively. Apart from the analysis of this research, Wagener et al. (2010) also argue that human actions are intrinsically part of the impacts on almost all parts of the current landscape worldwide.

It has already been indicated by many scholars that current engineering practice needs to be improved to better address the impact of human behaviour. Whereas it may seem impossible to *predict* human behaviour with the current state of knowledge, authors such as Sivapalan et al. (2012) and Ceola et al. (2016) argue that there is a need to develop better theories and methods to study the co-evolution of coupled human-water systems. Such a study may help in anticipating and capturing some of the plausible future dynamics related to human behaviour.

Although such a topic may not be new to the field of sociology, the use of knowledge about human behaviour (including human judgement and decision making) in flood defence engineering is still underdeveloped. Traditionally, human actions are mainly addressed in term of human errors causing some of the flood defence failure mechanisms. Hence, the focus is more on what can go wrong as a result of human actions on the system performance rather than what can enhance the performance of system (Hollnagel, 2014b). Furthermore, it is well known in the field of safety science that human errors are usually not quantifiable and not stochastic (Leveson, 2015). Taking advantage of human behaviour to better manage the risks threatening system performance is currently an important topic in safety science (Hollnagel, 2015). It is anticipated that the results of such an analysis can provide valuable information not only to reduce human error, as is common in flood defence engineering, but also to benefit from human capability to take corrective actions.

Perhaps one important direction for supporting adaptation planning for multifunctional flood defences under deep uncertainty (Lempert et al., 2003) could be to focus more on including human behaviour and further investigating the interactions between technical components, human actions, and environment as an integral part of developing multifunctional flood defences. In this regard, the proposed method in Chapter 5 (based on the FRAM approach) seems to be promising. FRAM is one of the state-of-the-art methods developed to explore the role of human actions on aviation safety (Hollnagel, 2012). It is strongly suggested that such (qualitative) methodology should be further improved and used, as complementary to reliability analysis methods, for performance analysis of multifunctional flood defences, with a particular focus on studying the role of human behaviour.

3) Need for addressing the mutual flexibility of flood defence and its secondary function(s)

The focus of this research is mainly on flexibility in the design and management of flood defences, especially as a means of handling sea level rise uncertainty. A multifunctional flood defence is, however, more than just a flood defence. Once a secondary function is combined with the flood protection function, the success and failure of the whole system becomes interdependent. For example, it is shown in Chapter 4 that considering the flexibility for each component of the system cannot be properly done in isolation from the other component(s). Similarly, Guariniello and DeLaurentis (2013) review the history of design and development of complex systems, where the overall system consists of many sub-systems. They conclude that these systems are often not designed in an integral way, meaning that the design considerations only address some predefined problems of the system.

In this regard, it is strongly suggested that while an improved design of the secondary function(s) can increase the flexibility of the flood defence, it is also required to address in what ways the flood defence design can increase the flexibility of the secondary function(s). Indeed, there is a need for a method to address the mutual interactions between the flood defence and its secondary function(s) similarly to the performance analysis methodology proposed in Chapter 5. The use of such a method, however, requires a collaborative approach in which a multidisciplinary team of designers and stakeholders should be involved in assessing the various possibilities for increasing flexibility for multifunctional flood defence.

4) Need for conducting more case studies of human-technical-environment interactions

This recommendation complements Recommendation number 3. To facilitate the design of, and in particular flexibility considerations for, multifunctional flood defences, the first step is to have a common frame of reference, i.e., a unified set of terminologies for the designers and managers of the flood defence and the secondary functions. The terminology and framework of Chapter 4 appears to be useful in structuring the discussion of flexibility for multifunctional flood defences. This framework however needs to be examined in real world case studies to diagnose its strengths and weaknesses and to further improve it.

Similarly, the performance analysis of this research (in Chapter 5) uses only one case study and addresses only one scenario of an extreme event. The alternative designs used in this case study are also simplified in order to facilitate the analysis process. Although the analysis results are used in Chapter 5 to make some preliminary conclusions, the results need to be verified in more real case studies including more scenarios.

Furthermore, the research presented in this dissertation is very theoretical. The majority of research results are based on investigating the limited number of publications available to the researcher. The results and conclusions of this research need to be further validated by conducting participatory research studies in which case-specific knowledge, expertise and reflections of various stakeholders can also be taken into account. It can be expected that examining the methodologies proposed in this research in a wide range of case studies including many different configurations of multifunctional flood defences may result in moving towards a generalisation of some research outcomes beyond the needs of specific cases.

5) Need for addressing and balancing flexibility, robustness and resilience

The literature review in Chapter 3 reveals that flexibility together with resilience and system robustness are three system attributes currently being used to handle uncertainty. It is observed that the interpretations of these attributes are not mutually exclusive and the enabling mechanisms overlap. Moreover, the term 'flexibility' is often understood intuitively in flood risk management literature, without a clear indication of its meaning and characteristics. To address this gap, this research is focused on exploring flexibility for multifunctional flood defences.

The cost-effectiveness study of Chapter 6 demonstrates that increasing flexibility in the design and management of multifunctional flood defences is not always advantageous. Similarly, in another study in the literature, Sakai and Dessai (2015) argue that adaptation planning with the aim of minimizing risks or returning to the pre-disaster levels of functioning is insufficient to manage uncertain climate change impacts. These observations raise a question under what conditions and to what extent each of the flexible, robust, resilient system attributes or combinations of them can be useful to handle uncertain future changes. There is currently a scientific debate about which approaches best suit adaptation needs although there is presently no standard procedure for selecting among them (Bisaro et al., 2016, Dessai and Hulme, 2004, O'Brien et al., 2007, Dessai et al., 2009).

So far, a few scholars have tried to address the required balance between different adaptation approaches. For example, Van Buuren et al. (2013) consider the need for balancing flexibility and robustness in the governance of adaptive spatial planning under climate change uncertainty. They suggest that system robustness (or resistance) is appealing when safety, durability and liability need to be guaranteed while (managerial) flexibility is more useful to enable adjusting policy strategies. However, their study does not address the case when an adjustment in policies requires a different safety standard to be implemented.

In another study, Van der Sluijs (2010) suggests that flexibility is required to address ‘anticipated imaginable surprises’ while robustness (indicating robust decision making approaches) is suitable to handle uncertainties when scenarios of future changes are available. However, it is still not clear when to use system robustness or resilience, and the use of flexibility to enable a better reactive response to changing conditions is not addressed.

Since the investment required to handle future changes is unknown, some scholars argue that it is the willingness of society to invest in being prepared, and the preferences of decision makers in charge of adaptation planning, that determine how to design for the future (O’Brien et al., 2012, Sakai and Dessai, 2015). The goal of scientific research similar to the research in this dissertation is to inform decision makers of the various possibilities to be prepared for future changes and to help them choose among them. While social preferences can be very influential in choosing and implementing adaptation, this argument does not help in deciding how to generate these strategies and how to support the development of a theory that can guide the process of adaptation.

One way in which further research can help decision makers to balance flexibility, system robustness and resilience is to generate a diverse set of options for handling uncertainty. These options should aim to improve the system capability to respond to change by combining different degrees of flexibility, resilience, and system robustness. Perhaps the use of a screening method as suggested before can be very handy to first analyse the sensitivity of the system components to change. Depending on how these components become impacted by various uncertain changes, a decision can be made between various mechanisms to enable flexibility, system robustness or resilience or a combination of them.

In order to be able to evaluate these options, there is a need to provide scientific guidelines with a clear indication of the different capabilities associated with each. A starting point could be to use the framework developed and proposed in Chapter 4. The four questions of the framework and the eight characteristic features can be adapted to compare the qualities associated with an option to increase the system resilience, robustness or flexibility.

8.2 Reflections and personal account

Along with my PhD research, I have come across some thought-provoking issues which were not directly related to my research questions. Therefore, I have not addressed them so far in my dissertation. Two of them are presented here.

1) Need to focus more on complexity than uncertainty

Flexibility has been applied in the case studies of this research to handle some anticipated future changes. The study of evolution of multifunctional flood defences in the past (Chapter 2), however, demonstrated that the evolution of many systems has been shaped by complex interactions between technical and physical components, human actions, and the environment of the system. It can be expected that the future of a multifunctional flood defence designed today can be unimaginably different from what we anticipate now. In such a complex situation, it is questionable to what extent current approaches for handling uncertainty can prepare the system to accommodate future changes.

Traditionally, the tendency of the engineering profession and decision makers is to reduce complexity and the dimensions of the problem to be tackled (Sterman, 2000, Nowotny, 2005, Suh, 2005). In doing so, scientific methods are developed that can only address a few aspects of a problem by making simplifying assumptions or ignoring the other aspects (Morss et al., 2005). For example, flood risk assessment methods do not address the complexity of interactions within the flood risk systems (Merz et al., 2015) and the cumulative impacts of human interventions (Lazarus et al., 2015).

Given that the multifunctional use of flood defences is aimed at more efficient use of land by combining different functions, the current tendency of designers and decision makers is to decouple these functions as much as possible in order to reduce the complexity and enhance controllability. Focusing on reducing complexity via decoupling the functional elements of a system is a well-known engineering practice (Suh, 2005, Dave et al., 2015). In the case of multifunctional flood defences, reducing complexity via decoupling seems to be at odds with the idea of multifunctional use of flood defences, which is about increasing the synergy between flood protection and urban development.

What can be inferred is that by focusing on uncertainty analysis and management through reducing complexity, a multifunctional flood defence may not become ready to handle future surprises. Future research should develop approaches for addressing and handling the complexities of interacting dynamics that can impact the desired performance of multifunctional flood defences. It has been suggested by authors in other fields that engineering practice need to embrace complexity, rather than attempting to reduce it (ElMaraghy et al., 2012).

With the goal of handling complexity, Coetzee et al. (2016) suggest the use of methods developed in the field of 'complex adaptive systems' (CAS) to analyse the non-linearity, aggregation, emergent behaviour, feedback loops, and autonomous adaptation to disastrous risks for developing context-based adaptation strategies. Pavard and Dugdale (2006) analyse the methodologies developed for studying the complexity of socio-technical systems and suggest that complementary to the methods that focus on the study of non-linearity, are the methods that focus on the study of distributed self-organizing systems. Such methods can help to better model the social processes impacting system behaviour. Therefore, in addition to embedding flexibility in the design and management of multifunctional flood defences to handle uncertainty, flexibility is also needed to effectively enhance the coping capabilities from the perspective that flood defences are complex socio-technical systems.

When the focus is on handling complexity, the purpose of flexibility will change. Following the framework of Chapter 4, the ways in which a multifunctional flood defence is required to be flexible (or the sources of flexibility determined) will be different. For example, the reinforcement strategies proposed in Chapter 6 are aimed at increasing the managerial flexibility to handle the anticipated gradual sea level rise. If, however, the goal is to handle emergent events that are neither predictable nor anticipated, then the required flexibility might be to enable a quicker reaction to change. Or, perhaps, the timeframe of the flexibility required (operational, tactical and strategic) to respond to such emergent situations will be different.

2) Need for changing the evaluation process

The evaluation of flexibility in Chapter 6 was carried out for the analysis period of 100 years. The intention of considering flexibility was to maintain a minimum level of safety during this period, but the possible changes in safety standards were not addressed. It can be claimed that the underlying assumptions in the evaluation model of this research as well as in similar economic appraisal studies can seriously affect the validity of such an analysis. Subsequently, the use of such results for informing decision makers can also become questionable.

Today, there are many different methods and criteria developed to support the evaluation and ranking of the generated adaptation strategies. Since the benefits of adaptation are expected to be realised over several decades, the analysis period is also chosen to be in the order of the same length of time. Given that the future can develop in many different ways, the anticipated changes in a strategy are also addressed in scenario-based evaluation approaches. While it can be useful to identify and prove the usefulness of a specific strategy over the long term, it is claimed here that the results of such an evaluation (estimated over a long period of time) should not be used to choose among the generated strategies.

As an example, moving on a decade from the start of a large project (such as in the case of Afsluitdijk) the project's objectives (e.g. because of changing societal preferences) can change before the initial project is even completed. If the initial design of a system has been chosen based on an evaluation of that specific design over a period of more than 50 years, it can be judged that such project has failed to achieve its goals as stated in the initial evaluation process.

One may claim that the use of many different scenarios can help in anticipating many different future possibilities. The evolution of multifunctional flood defences as presented in Chapter 2 shows that some of the most significant changes in the system have happened after a fully unexpected event occurred. For example, it can hardly be imagined that the initial designers and decision makers of the Afsluitdijk would have thought of experiencing two world wars in one century.

Separately from this research, Sivapalan and Blöschl (2015) have reviewed a century of changes in water resource management. Their review shows that the preferences of water resource managers have changed chronologically from single purpose projects to multi-objective projects (Russell and Baumann, 2009), from an emphasis on structural measures to an emphasis on incorporating ecological values into water policy (Gleick, 2000), from short-term goals to longer time scale outlooks (Loucks, 2000), and from solely politics and expert-driven decision making to an increased role of community participation (Ivey et al., 2004, Carr et al., 2012).

The scenario-based approaches such as ‘Exploratory Modelling’ (Agusdinata, 2008) are aimed at investigating the performance of a set of strategies over a large number of plausible scenarios. To my knowledge, they are not used to address drastically (and unimaginably) different changes in the world. Indeed it is not feasible to generate and address an unlimited number of future possibilities. Additionally, the decision making process cannot be guided by imaginary scenarios describing a very strange future (as in science fiction books), even if they materialize in reality. While the current use of scenarios can greatly help in investigating the potential of a strategy, it is emphasized again that the results of any evaluation model over a long period of time can be seriously unreliable. With the current state of knowledge, any evaluation model includes some static assumptions and, therefore, it is ignored that the values and preferences of decision makers and society can change in fully unknown ways.

One way to address the changing preferences and values in the evaluation process can be to shorten the analysis period of the evaluation model during the process of ranking the generated strategies. It is admitted that the evaluation of long term strategies should be for a long period of time. It is, however, strongly suggested that the cost-benefit analysis should be conducted for a carefully chosen, short analysis period. Fewer time-dependent criteria should be developed and applied for evaluating the long term benefits of a strategy. For example, a decision criterion such as the ‘regret’ value may appear to be less time dependent, which is true if this regret value is only quantified in the near term future. Otherwise, one would need to clarify the meaning of a low regret strategy, taking into account the unpredictable changes in the objectives of a project in the future.

Apart from the abovementioned issue, the evaluation process of Chapter 6 suffers from another limitation in relation to the effects of the lifespan considered. For example, if the lifespan of the secondary function is shorter than the reinforcement design lifetimes and the secondary function does not exist at the time of reinforcement then, at that time, the dike can be considered as a mono-functional flood defence. If the choice of reinforcement strategy has not taken this into account, the anticipated required reinforcement measure (e.g. sheet pile) will be different from the required reinforcement measure (e.g. normal dike widening and heightening) in the future. The situation will become very complicated when taking into account that the secondary function might be replaced by another (perhaps unknown) function in the future if a long analysis period of (typically) 100 years is chosen initially.

Acronyms

km: kilometre

m: meter

€: euro

Yr: year

M€: Million euros

CPB: Netherlands Bureau for Economic Policy analysis

CIRIA: the Construction Industry Research and Information Association

Defra: Department for Environment, Food and Rural Affairs

EEA: The European Environment Agency

FMEA: Failure Mode and Effect Analysis

FAO: Food and Agriculture Organization

FTA: Fault Tree Analysis

FRAM: Functional Resonance Analysis Method

INCOSE: De International Council on Systems Engineering

IPCC: Intergovernmental Panel on Climate change

KNMI: Koninklijk Nederlands Meteorologisch Instituut, meaning "Royal Netherlands Meteorological Institute"

MA: Millennium Ecosystem Assessment

NAP: Normaal Amsterdams Peil, meaning 'Amsterdam Ordnance Datum'

OCED: The Organisation for Economic Cooperation and Development

SLR: Sea Level Rise

TAW: Technische Adviescommissie voor de Waterkeringen, meaning 'Technical Advisory Committee on Flood Defences'

Glossary and definition of terms

Adaptation: The process that entails responding to uncertain changes in drivers, pressures and impacts on a system.

Adaptation Pathway: A sequence of responses and potential adaptations.

Adjustment: A process to respond to change via modifications in a system configuration.

Approach: The main orientation

Climate proofing: A process aimed at enhancing the resilience of a system or a component of the system to climate change.

Design lifetime: the duration of time during which a flood defence satisfies its desired performance.

Dike: a predominantly earth, structures constructed for the purpose of water retaining.

Driver (of change): natural or human induced process that that has resulted in tangible land use change.

Emergence: The arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems.

Flexibility: the capability of a system to be easily (performance-efficiently, cost-effectively, timely) adjusted.

Flood defence: a physical structure used to retain water.

Flood protection zone: the area around a flood defence reserved for future reinforcements.

Land use: the purpose of a piece of land allocated to multifunctional use.

Land use change: major visible adjustments in the function, size, and existence of a **multi**functional flood defence over time.

Maladaptation: An action taken supposedly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups.

Method: A systematic (i.e., stepwise) process of analysis.

Multifunctional dike: A multifunctional flood defence where the flood defence is a dike.

Multifunctional flood defence: the flood protection zone of a flood defence used to serve secondary non-water retaining function(s).

Multifunctional flood defence (evolved): a specific area that was initially constructed to operate one function, but evolved to have a flood protection and some additional functions.

Multifunctional flood defence (planned): the situation in which the intention of multiple use of the land had been embedded in the development plan from the beginning.

Net Present Value: The sum of the discounted benefits of an alternative less the sum of its discounted costs, all discounted to the same base date.

Real Option: The right but not the obligation to adjust a system or a component of the system to future uncertainties when these unfold.

Resistance: The system capability to withstand change during the occurrence of extreme events.

Resilience: The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks, and therefore identity; that is, the capacity to change in order to maintain the same identity.

Return period: The average number of years within which an event is expected to be equalled or exceeded only once.

Risk management: The culture, processes and structures directed towards realising potential opportunities whilst managing adverse effects.

Robustness (system): The system capability to resist during the occurrence of extreme events without the need for any system reconfiguration.

Scenario: Plausible and internally consistent view of the future, which is used to explore uncertain future changes, the potential implications of change and the responses to these.

Socio-Technical system: All the physical systems, actors and rules required in order to perform a particular function.

Strategy: a plan designed to achieve a particular long-term goal.

System (multifunctional flood defence): the combination of technical & functional components of a multifunctional flood defence and the local actors.

Threshold: The critical value of an indicator at which specific potential adaptation action is required.

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