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Cascade effects in critical infrastructure

Predicting failure from flood events in interdependent infrastructure networks

Martijn Krol

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CASCADE EFFECTS IN CRITICAL INFRASTRUCTURE

Predicting failure from flood events in interdependent infrastructure networks

MASTER THESIS IN
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Abstract

Interdependency within and between critical infrastructure networks increases their vulnerability to failure after a natural hazard such as a flood event. When operation of infrastructure assets gets disrupted this can trigger failure in other infrastructure assets. This process is called a cascade effect and can happen recursively which can cause initially small infrastructure disruptions to have widespread consequences.

This study aims to predict cascade failure occurrence due to floods in a selected set of infrastructure networks at a detailed spatial scale. Using a given inundation map to assess direct failure of assets, interdependencies between them are used to simulate indirect failure, i.e. assets failing due to a cascade effect. Failure is described using a topology-based simulation model with aboveground infrastructure assets represented as nodes and interdependencies between them as edges.

The modeling methodology is applied for the electrical, telecoms, gas and transportation networks in the Dutch region Zeeuws-Vlaanderen. However, the aim is to devise a method which is generically applicable both in other locations and other types of networks. In order to assess model validity and determine potential areas of improvement, model results and premises are discussed in an expert elicitation process. Operators of selected infrastructure networks are asked to comment on differences between simulated and realistic failure behavior that ensue from modeling choices.

In the case study, failure occurs mostly around inundated areas, with direct failure generally accounting for the larger share. This is attributed to key assets in selected networks not being vulnerable to flooding due to their geographical location, but also to the absence of higher order networks in the case study. Indirect failure mostly occurs from intra-sectoral cascade effects, so interdependence between different infrastructure networks is not a driving force behind widespread failure. Vulnerability to cascade effects can be reduced by introducing more network redundancy.

While this modeling methodology attempts to be generically applicable, differences between infrastructure networks are encountered that require custom-fit modeling approaches. More information specific to locations and networks can be introduced, but this does institute a need for additional assumptions and data which is often unavailable. The currently applied modeling methodology generally performs well in determining asset functionality during flood events, especially in networks with a clearly defined function and network commodity. However, it falls short for more complex analyses as these require more network- and location-specific modeling. The largest sources of inaccuracy are the premise that no network flow is modeled and the connection with infrastructure networks of higher order, such as the high voltage and national gas networks.

Nederlandse samenvatting

Afhankelijkheden binnen en tussen kritische infrastructuur maakt dit type netwerken gevoeliger voor uitval na een natuurramp, zoals een overstroming. Als bepaalde infrastructuur niet meer kan functioneren kan dit ook uitval van andere infrastructuur veroorzaken. Dit proces wordt een cascade effect genoemd. Deze effecten kunnen recursief optreden waardoor verstoringen in infrastructuur die initieel klein zijn tot wijdverspreide problemen kunnen leiden.

Deze studie heeft als doel uitval door cascade effecten die optreden door overstromingen met een hoog detailniveau te kunnen voorspellen. Directe schade wordt bepaald aan de hand van een gegeven inundatiekaart, waarna de afhankelijkheden tussen infrastructuur gebruikt worden om indirecte schade die optreedt door cascade effecten te bepalen. Uitval wordt in kaart gebracht met een topologie-gebaseerd simulatiemodel waarin bovengrondse infrastructuur is opgenomen als knopen en de afhankelijkheden als zijden.

Deze methodologie wordt toegepast voor het elektra-, gas-, telecom- en transportnet in de Nederlandse regio Zeeuws-Vlaanderen. Het doel is echter om een methode op te stellen die generiek toepasbaar is voor zowel andere locaties als netwerken. Om deze methode te valideren en potentiële verbeterpunten vast te stellen worden modelresultaten en uitgangspunten besproken in een expert elicitatie proces. Netwerkbeheerders in het studiegebied wordt gevraagd hoe modelkeuzes verschillen tussen werkelijke en gesimuleerde netwerkuitval veroorzaken.

In het studiegebied komt uitval van infrastructuur voornamelijk voor in overstroomde gebieden, waarin het grootste deel door directe schade wordt veroorzaakt. Dit komt doordat de belangrijkste infrastructuur in het gebied niet gevoelig is voor overstromingen maar ook doordat netwerken van hogere orde in het studiegebied niet zijn meegenomen. Indirecte uitval komt voornamelijk voort uit gevolgen binnen een enkel netwerk, afhankelijkheden tussen verschillende netwerken veroorzaken geen wijdverspreide uitval. Kwetsbaarheid voor cascade effecten kan beperkt worden door meer redundantie in netwerken in te bouwen.

Hoewel het doel is om de methode generiek toepasbaar te laten zijn, zitten er sommige verschillen tussen infrastrucuur die specifieke modeleermethodes voor bepaalde netwerken vereisen. Het is mogelijk nog meer informatie specifiek voor bepaalde netwerken en locaties in het model onder te brengen maar dit vereist nieuwe aannames en data die vaak niet beschikbaar zal zijn. De gebruikte methode is, vooral in netwerken met een enkele duidelijke functie, goed in staat om locatiespecifieke uitval in kaart te brengen. Voor complexere analyses schiet deze methode echter tekort omdat hier meer locatie- en netwerkspecifieke kennis voor nodig is. De meeste onnauwkeurigheid wordt veroorzaakt door het uitgangspunt dat er geen stroming over het netwerk gesimuleerd wordt en door de koppeling met netwerken van hogere orde, zoals het hoogspannings netwerk en het nationaal gasnet.

Preface

This report is the final product of my graduation internship at Nelen & Schuurmans and coincidentally it is also the final product I make to complete my studies in Water Engineering and Management at the University of Twente. Finishing this report marks the end of my time as a student which I have very much enjoyed over the past six years. I have had great experiences and met wonderful people and would like to thank everyone involved in this period of my life.

The report you are reading could not have been made without the help of some people. Firstly I would like to thank everyone at Nelen & Schuurmans for the warm welcome I have received. The people here kept me motivated to continue working on my thesis over the past six months. In particular, I want to express my gratitude to Jelle for his helpful guidance and attention to detail, and to Anne for keeping me focused on the bigger picture. I also want to thank my supervisors Jord and Maarten, without their feedback and critical attitude I would not have been able to complete this report. Lastly, I would like to thank all the experts I interviewed in this study for their valuable input and comments.

I hope you enjoy reading my thesis!

Martijn Krol

Utrecht, June 2018

Contents

1 | Introduction

Quality of life and the functioning of society depend on services provided by critical infrastructures. Espada et al. (2013) define critical infrastructure as the physical facilities, technological networks and logical systems that have major importance for public welfare. Examples of critical infrastructure sectors are electricity, transportation and telecoms. These infrastructures are mutually interdependent, i.e. functionality of one infrastructure depends on the functionality of others and vice versa. Lee et al. (2007) note that this interconnectedness between critical infrastructure has increased over time.

Interdependency between infrastructures can lead to cascade effects. When one infrastructure is unable to provide its service due to a natural hazard or other cause, this can lead to failures in other infrastructures. This effect can happen recursively causing a chain reaction called a cascade failure, which can potentially result in complete system breakdown (Kotzanikolaou et al., 2013). Buldyrev et al. (2010) demonstrate that increased interdependency between systems also increases their vulnerability to failure from cascade effects. Small disruptions in infrastructure can spread beyond themselves and cause notable disturbances in other infrastructures (Little, 2002). Furthermore, interconnectedness in infrastructure can provoke disruptions distant from the initial failure. An example of such an effect is provided by O'Rourke (2007) who describes how production of gasoline was disrupted in the Midwest of the United States after hurricane Katrina, which made landfall in Louisiana.

This study focuses on cascade effects that occur after a flood event in infrastructures with a physical network structure. These infrastructures have assets with a physical location which are interconnected. While some connections are straightforward, others are more intricate. In a modeling sense, these assets are regarded as nodes and the connections between them as edges in a network structure. In this way, infrastructure networks form complex systems which consist of numerous nodes that are mutually interdependent. Relationships between these nodes are marked by uncertainty and unpredictability (Liu et al., 2015). This intricacy hinders prediction of cascade failures and burdens the inclusion of resilience in critical infrastructure network design.

Studies on cascade failures typically aim to characterize and categorize infrastructure interdependencies. Ouyang (2013) notes that the terms dependency and interdependency are used interchangeably in literature. Therefore the term interdependency can describe both a unidirectional and a bidirectional relationship between infrastructure assets. Numerous different classifications have been applied to describe interdependencies in infrastructure (Rinaldi et al., 2001). To avoid confusion, this work chooses to use a twofold categorization. The first classification discerns interdependencies as either existing within a single network (intra-sectoral) or between networks (inter-sectoral). The second classification is proposed by Dudenhoeffer et al. (2006) and is based on the functional nature of an interdependency. An overview of interdependency classes is shown in Fig. 1.1.

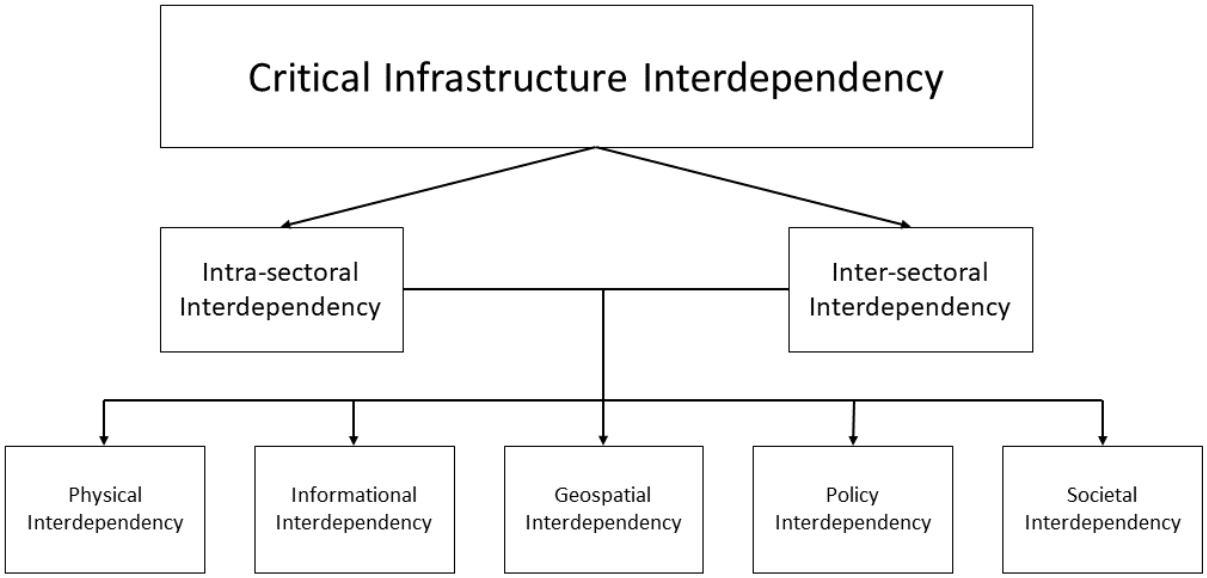

Fig. 1.1: Categorization of Interdependencies

Within the classification by Dudenhoeffer et al. (2006) five classes are defined. A physical interdependency describes a direct relation between two infrastructures. If a is physically dependent on b, failure in b will also halt functioning of a. An informational interdependency describes some information requirement that an infrastructure needs for operation. Absence of this information does not result in immediate failure of the infrastructure but may in some way impede its functionality as control of the operation is hampered. Infrastructures are geospatially interdependent when they can be affected by the same local effect due to proximity. Kotzanikolaou et al. (2013) call this local effect a common-cause failure, an event which can cause concurrent disruption in multiple critical infrastructures. In a flood context this means they can be damaged as a result of the same flood event. The latter two interdependency classes describe governmental policies or societal effects which can affect infrastructure operation. These interdependencies are generally less prevalent in physical network cascade failure and will therefore not be regarded in this work.

1.1 Objective

The aim of this study is to implement and test a modeling methodology which can be used to simulate cascade failure in physical infrastructure networks that results from a flood event. Hereto interdependencies within and between a number of selected infrastructure networks are modeled. Interdependency modeling is done at a component level, so at the level of infrastructure assets. This allows prediction of failure on a detailed spatial scale, being town or street level. This model is tested by application in a case study in order to see to what extent cascade effects occur in a flood scenario. However, the goal is to formulate a modeling methodology which is generically applicable for both location and choice of infrastructure networks. Model results in the case study are used to give an indication of model applicability in a wider sense. Sensitivity analysis and an expert elicitation process are used to determine whether model results adequately resemble infrastructure failure behavior and to assess in what situations the current modeling methodology is applicable.

1.2 Research questions

1. How can infrastructure interdependencies be represented in the context of a flood simulation model and what modeling choices are made in this process?
2. To what extent can cascade failures after flood events be simulated using infrastructure interdependency modeling?
3. How do modeling choices and assumptions influence simulated cascade failure?

1.3 Scope

This thesis focuses on creation and testing of a model which is able to predict failure in multiple critical infrastructure networks resulting from a given flood event. The aim is for this model to be generically applicable, so suitable for multiple networks and locations. This model is constructed and tested using a case study with five interdependent critical infrastructure networks.

Two modeling cases are regarded to analyze cascade failure. In the first case the temporal component of a flood event is ignored, meaning duration and development of a flood are disregarded. The second case does introduce a temporal component to the model, so here time related flood parameters are taken into account. When these temporal flood data are considered, also mitigation operations which can be employed during the flood event to reduce the impact of cascade effects can be simulated.

With the implementation of interdependencies within and between infrastructures into a modeling context, choices and assumptions are made. This process influences the simulated level of cascading effects that develop from a flood event. Identification of modeling choices and analysis of their role in cascade failure occurrence is regarded as an important indicator of model result accuracy.

Influence of modeling choices is analyzed in two ways. When a modeling choice can be characterized by a certain parameter, a sensitivity analysis for this parameter is performed. When parametrization of a modeling choice is unfeasible, its influence is discussed with operators of infrastructure networks in the case study area. An expert elicitation process is performed to use their local expertise to analyze the role of various modeling choices on simulated cascade failure.

1.4 Report outline

Following this introductory chapter, the next chapter describes the methodology employed in this study. Consecutively, chapter 3 describes model results of simulated cascade failure under selected conditions in the case study area. Both results for the reference case and the findings of the sensitivity analysis are provided here. Chapter 4 describes the results of the expert elicitation process. Chapter 5 discusses findings of this study after which conclusions and recommendations are provided in chapter 6.

2 | Methodology

This chapter describes the methodology applied to answer the research questions posed in section 1.2. Firstly, the model which is used to simulate cascade effects after a flood event is described. After this, the method of implementation in a case study, the sensitivity analysis and the expert elicitation process are specified.

2.1 Simulation model

Failure in critical infrastructure is regarded using a topology-based simulation model. This approach has a strong focus on physical network structure of critical infrastructure, making it ideal for modeling failure at an asset level. The first section of the methodology will detail the choice for this model and its functionality.

2.1.1 Model selection

In advance of this study three interdependency modeling approaches out of the selection by Ouyang (2013) are selected for potential application in this study. These models can be used to model interdependencies between critical infrastructures and simulate cascade effects. A summary of the potential model approaches and the selection process is provided in this section. An overview of investigated modeling approaches is shown in Table 2.1.

Table 2.1: Overview of modeling concepts, data requirements and results of potential infrastructure interdependency models

<table>
<tr><th colspan="2">Approach</th><th>Modeling Concept</th><th>Input Data Requirement</th><th>Model Results</th></tr>
<tr><td colspan="2">Empirical</td><td>Use of historical failure to identify typical patterns</td><td>Historical failure data</td><td>Failure patterns at system level</td></tr>
<tr><td colspan="2">Agent based</td><td>Autonomous agents simulate complex system behavior</td><td>Rule sets for various agent types</td><td>Cascade effects at component level</td></tr>
<tr><td rowspan="3">Network Based</td><td>Topology-based analytical</td><td>Simulate network failure through segregation</td><td>Network topology and dependencies</td><td>Set of segregated networks</td></tr>
<tr><td>Topology-based simulation</td><td>Simulate network failure through losing connection to source nodes</td><td>Network topology with differentiation between nodes</td><td>Binary indication of asset functionality</td></tr>
<tr><td>Flow-based</td><td>Simulate operation by modeling commodity flow over network links</td><td>Network topology with production and flow characteristics</td><td>Cascade effects at component level</td></tr>
</table>

Empirical models

Empirical methods try to predict cascade effects by analyzing previous occurrences. Because interdependencies between critical infrastructure are often difficult to identify under normal operation (Ouyang, 2013), regarding previous occurrences of failure can provide a more complete understanding of failure patterns.

Empirical model approaches typically use a database containing information about previous failure. These databases are typically only applicable to regard failure at a system level. Chou and Tseng (2010) also apply an empirical approach to regard failure at the component level of critical infrastructure. However, a lack of relevant data which is standardized and harmonized hinders application of empirical approaches to predict failure in a case study. Especially in a flood context the data availability regarding failure in critical infrastructure is low as well-documented accounts of infrastructure behavior under hazard conditions are scarce.

Agent based models

Agent based modeling (ABM) aims to solely model the units of a system in order to derive and analyze overall system behavior (Kaegi et al., 2009). These units, called agents in ABM approaches, interact with each other and their environment through a set of relatively simple rules.

A disadvantage of ABM in the classification by Ouyang (2013) is that it typically does not account for topological properties of infrastructure. This makes them not very suitable for regarding failure that results from a flood event. Nonetheless, this difference between ABM and network based models is not very well defined and combinations of these approaches have been applied (Dudenhoeffer et al., 2006). Another disadvantage of ABM is that it requires a thorough understanding of network failure processes in order to supply rules to the agents.

Network based models

The last category focuses on the network structure of critical infrastructure. Herein infrastructure assets are modeled as nodes and interdependencies between them are regarded as edges. Together these form a graph, allowing the simulation of network failure by using graph theory (Buldyrev et al., 2010). Network based models can be subdivided into topology-based analytical, topology-based simulation and flow based approaches.

Topology-based analytical approaches model nodes of critical infrastructure homogeneously, i.e. there is no differentiation between nodes of single networks. When nodes are removed from this network due to a natural hazard or attack, nodes that share interdependencies with them also fail. Node differentiation is applied in topology-based simulation approaches which introduces a distinction between source and demand nodes. This allows for modeling failure that occurs when infrastructure assets lose access to a source. Lastly, flow based models also regard flow over a network. This makes it able to take production and transportation capacity into account. These approaches have an increasing level of detail in model results, but also an increasing data requirement.

Selection process

Out of the investigated modeling approaches the topology-based simulation approach got the preference. All network based models have a strong focus on infrastructure assets and their location.

This makes these approaches very suitable to analyze failure that results from flooding, as this is a strongly location based phenomenon. Furthermore these approaches are very suitable to analyze infrastructure functionality with a high level of detail as failure is regarded at the level of assets.

The reason a topology-based simulation approach is selected out of the three network based models, is that it can be set up in a generic way to model failure in different infrastructure networks. This eases inclusion of multiple networks into a single modeling context and makes this approach especially suitable for modeling interdependency at a component level in physical networks. Another advantage of the selected approach is that data about infrastructure networks in a case study which fit this approach was readily available. Lastly, this approach has had documented success in cascade failure simulation after natural hazards (Dudenhoeffer et al., 2006; Dueñas-Osorio et al., 2007; Adachi and Ellingwood, 2008).

2.1.2 Model approach

As stated topology-based methods formulate networks by describing infrastructure assets as nodes and the interdependencies between them as edges. This approach is applied for multiple networks. Therefore, a generically applicable network structure needs to be defined that can be used to describe failure in different networks. This section reflects on the definition of networks and how failure is simulated using this network structure.

Model schematization

To describe critical infrastructure as networks, their aboveground components are regarded as nodes which have a physical location. These nodes are connected by edges which describe interdependencies. To use this approach for multiple networks simultaneously, the schematization of Buldyrev et al. (2010) is applied. A node can only be part of a single network but edges can exist both within a network (intra-sectoral) and between two different networks (inter-sectoral). A visualization of this network structure is shown in Fig. 2.1.

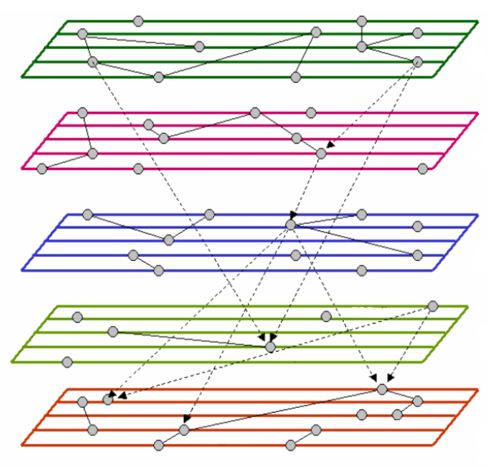

Fig. 2.1: Visualization of infrastructure network anatomy, edited from Dudenhoeffer et al. (2006). Different layers represent infrastructure networks with nodes depicting assets and edges depicting interdependencies. Both intra-sectoral (solid lines) and inter-sectoral (dashed arrows) interdependencies exist.

Within the topology-based simulation approach a distinction is made between source and demand nodes. Source nodes produce the network commodity, e.g. power plants in the electrical network. Demand nodes receive this commodity and require it to maintain operation. For this reason all demand nodes must be connected to a source under normal conditions. In a typical network structure, the number of demand nodes exceeds the number of source nodes. Consequently, one source typically supplies a large number of demands. Demand nodes might receive the network commodity from a single source, or they can be connected to multiple sources. The selected modeling approach places strong emphasis on the distinction between source and demand nodes, requiring sources and demands to be appropriately defined in each infrastructure network.

An infrastructure network is defined as a set of nodes and edges that provides a single commodity. Within this general schematization, networks can have varying structures and properties. For this reasons also different failure patterns exist in infrastructure networks. Paragraph 2.1.4 reflects on the intrinsic differences that exist between infrastructure networks and the modeling implications of these differences.

Failure simulation

Two failure types are defined in this modeling approach; direct failure which occurs when a node comes into contact with water and fails as a result, and indirect failure which is a node failing due to a cascade effect. Indirect failure can both be a demand node losing access to the network commodity (intra-sectoral cascade) or occur because of a dependency on an asset of another network (inter-sectoral cascade).

Failure is simulated for each network separately in an order that should be decided based on what inter-sectoral interdependency exists between selected infrastructure networks. Fig. 2.2 shows the procedure for failure simulation in a single network. This is a general structure, so slight differences exist depending on the intra- and inter-sectoral interdependencies that exist in a network.

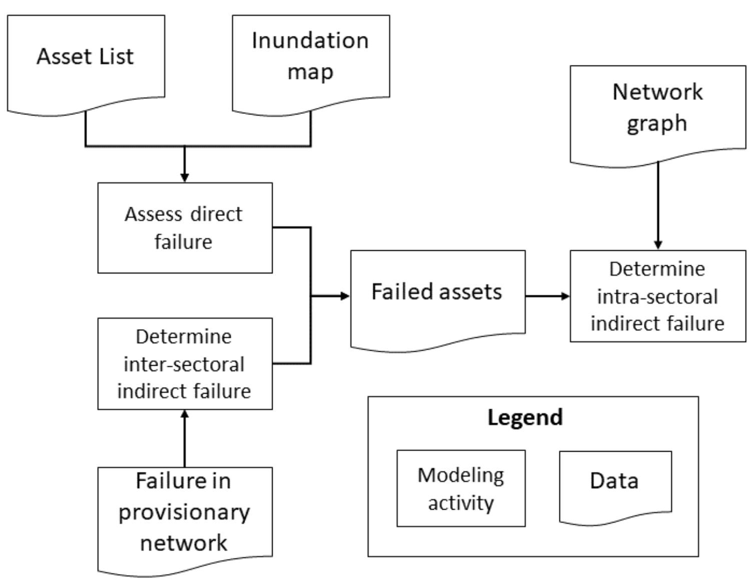

Fig. 2.2: Generalized modeling structure of failure simulation in a single model, deviations exist per network.

The first step for each network is the simulation of direct failure, which is assets failing due to contact with a flood event. Generally this will occur at nodes but it can occur at every aboveground infrastructure asset, so also at edges. Assessing whether an asset fails is done by comparing asset location with a flood map. In this assessment, inundation depth of assets is the only parameter considered. Every network asset that can fail has an assigned critical water depth. When the water level caused by a flood event exceeds this critical water depth this results in direct failure. This is the practical implementation of geospatial interdependency in the modeling context.

Every asset which fails directly is removed from the network structure. After this an analysis if performed what other assets fail as a result of the direct failure. Every node at which the critical water level is not exceeded but which still loses functionality is considered indirectly failed. After direct failure, effects of inter-sectoral cascades are examined. When an asset has a physical dependency on a failed asset of another network, it fails indirectly. The last step describes the effects of intra-sectoral cascades. All assets that fail in the previous two steps are removed from the network, after which an analysis is performed whether demand nodes are still connected to a source node. Demand nodes that become disconnected from all their source nodes also fail indirectly. Appendix B contains a flowchart detailing failure simulation in the model over all selected networks in the case study.

Temporal modeling scope

The failure simulation described in the previous paragraph can be performed in two different contexts. In the first and most simple case no temporal component is included in the model. This means time related parameters of flood events are ignored and a single inundation map is used to regard failure. This is typically a map with maximum inundation depth reached during a flood event. An analysis without a temporal component can be used to give a global indication of the impact of a flood event on infrastructure networks.

In the second case, temporal flood parameters are used to analyze development of network failure over time. Here, instead of maximum inundation depth, flood maps contain inundation depth per time step. By default a time step of 1 hour for a total of 48 hours is used. A temporal component is included in the model to show when failure will occur in different infrastructure at what locations. In this case failure simulation is executed at every time step. For appropriate networks this can also include storage of assets which fail directly. When a critical water depth of an asset is exceeded in one time step but the water level drops in a subsequent time step, this asset is unlikely to become functional again. Therefore, directly failed assets are stored and kept as such throughout the simulation. Since for some networks assets can become functional again after becoming uninundated, the storage of directly failed assets is optional per network.

2.1.3 Model premises

The previous paragraph describes the general method in which cascade effects after flood events are simulated. This general method is applied for numerous infrastructure networks which are different by nature and thus have varying failure behavior. In order to uniformly describe cascade effects in different infrastructure networks in a similar manner, model premises are introduced. These premises simplify failure behavior allowing a uniform approach to failure simulation.

Only selected asset failure

During a flood event, only failure in selected assets is considered in this modeling approach. These are generally nodes, which are model representations of aboveground assets which can be directly affected by a flood event. Any other asset which might be critical in network operation is not considered for failure. This includes mostly edges which are used to describe interdependencies, such as underground ducts or cables. In reality these assets can also fail, which might cause differences between simulated and realistic consequences of flood events.

Inundation depth as only fail criterion

Following the most basal approach in flood damage modeling (Jongman et al., 2014), inundation depth of assets is the only parameter that decides direct failure. Some other parameters that are occasionally included alongside inundation depth to assess flood damage are flow velocity, inundation duration, water contamination and preparation time (Jongman et al., 2012). In this analysis these parameters are not taken into account for the determination of direct failure.

Binary failure

Besides failure only being able to occur in selected assets, another model premise is that only binary failure is possible. This means an asset either has full functionality or has completely failed. Within the topology-based simulation approach it is impossible to model the diminished functioning of assets. Both direct and indirect failure of assets are possible, but in both cases this implies that an asset has completely lost all functionality.

No flow simulation

In the topology-based simulation approach all network parameters are assigned to nodes. Unlike typical spatial networks, in this model edges typically contain no information beyond which nodes they connect (Barthlemy, 2010). This changes when edges have the possibility to fail, but in this case the only information assigned to them is a critical water depth.

Correspondingly, source nodes produce the network commodity but do not have a value assigned to their production capacity. Transportation from source nodes over edges to demand nodes is not simulated and functionality is purely decided by connectivity (Ouyang, 2013). A consequence of this premise is that demand nodes always remain functional when connected to a source node, irregardless of connection route. Hence, in the model a single source node is able to provide for all connected demand nodes as long as a connection route is available. Hines et al. (2010) show this is usually an overly optimistic view for electrical networks. Another case where this simplification might lead to inaccuracy is in transportation networks, where if a village can be reached via only a small road it is considered accessible because the model is unable to account for congestion that would occur in realistic scenarios.

Scope limitation

The final premise is that simulated failure is limited to a selected modeling scope. Only processes that take place inside and between selected networks in a study area can influence network failure in the model. Any interaction with infrastructure networks which are not implemented in the model can thus also not drive failure. Furthermore, assets which are outside the study area do not influence failure processes within the study area. This makes it important to appropriately select the boundaries of a case study area. This premise is mostly relevant for relationships with national networks. These often have few or no assets within a study area, but failure in these networks can cause complete collapse of infrastructure. Therefore, influence of this premise depends on the study area and selection of infrastructure networks.

2.1.4 Network properties

While the general approach to failure modeling is uniform for all networks, some differences between infrastructure networks are encountered which require custom approaches. This section lists different properties of infrastructure networks which result in differences between the nature of cascade effects. This list is based on the networks encountered in the case study as described in section 2.2, making it inherently incomplete. However, since the infrastructure networks implemented in the case study are among the most essential in studies towards cascade failure (Van Eeten et al., 2011), it provides an adequate overview of fundamental differences between infrastructure networks.

Type of asset failure

In the modeling context assets fail due to an inundation level exceeding their critical water depth. These assets which fail therefore have to be aboveground. In the modeling context this failure can thus happen at either nodes or edges. Examples for both encountered in the case study are aboveground transformer stations in the electrical network as failing nodes and roads in the transportation network as failing edges.

All failure in a network is expressed in assets which are able to fail directly. So in networks where nodes are susceptible to flood damage, also indirect failure is expressed in the nodes. Similarly when edges can fail directly, indirect failure is also measured at the network edges.

Network structure

Infrastructure networks are defined as a set of nodes and edges that provide a single commodity. Networks can be completely interconnected but can also consist of multiple sub-networks which operate independently of each other. Here a sub-network is defined as a set of nodes and edges which contains at least one source node and is disconnected from the rest of the network. Since source nodes can also connect to assets of other networks or to direct consumers, there is no requirement for a sub-network to contain a demand node. For this network property three options are specified which are visualized in Fig. 2.3.

- Interconnected: All assets in a network are connected to each other.
- Mixed: The network is not completely interconnected but also not fully fractured. Some sub-networks which are served by a single source exist but some source nodes might also be interconnected.
- Sub-networks: The infrastructure network is completely fractured. Source nodes are not connected among each other and all demand nodes are connected to a single source.

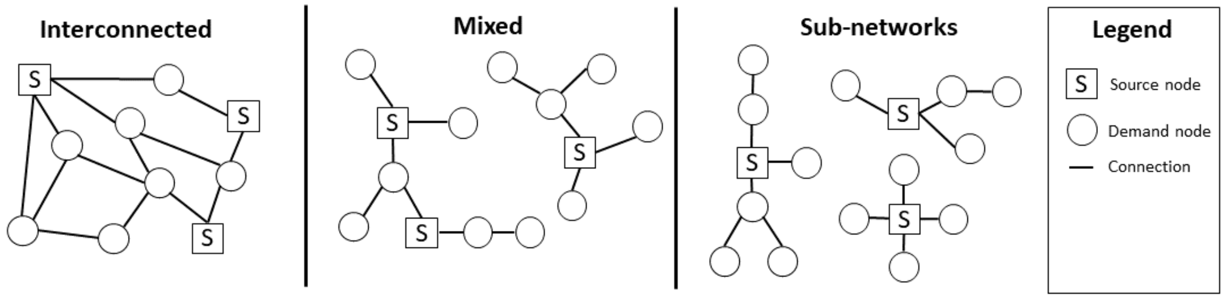

Fig. 2.3: Overview of different possibilities in the way infrastructure networks are structured.

Demand node connection

There exist differences between infrastructure networks in how demand nodes connect to a source. These differences exist for numerous reasons such as general network structure, existence of safety fuses and other fail safes. Because of the differences in demand node connection, infrastructure networks differ in how failure in a demand node impacts surrounding nodes. Source nodes are always encountered to be a fail safe, so failure in a demand node can never trigger a failure of a source in the same network. Three different options are encountered for this property. For networks in which failure occurs in nodes, these different options are displayed in Fig. 2.4. For clarification, in all three cases failure of the source node triggers indirect failure of all demand nodes.

- Individual: Every demand node is connected individually to a source. Failure in a demand node does not trigger any effects in other demand nodes.
- Series: Demand nodes are connected in a series from a source. Failure in demand nodes occurs if no route to a source through other functional demand nodes is possible.
- Clustered: Demand nodes occur in interconnected clusters with a single connection to a source. If any demand node in the cluster fails directly, all other nodes in the cluster also fail.

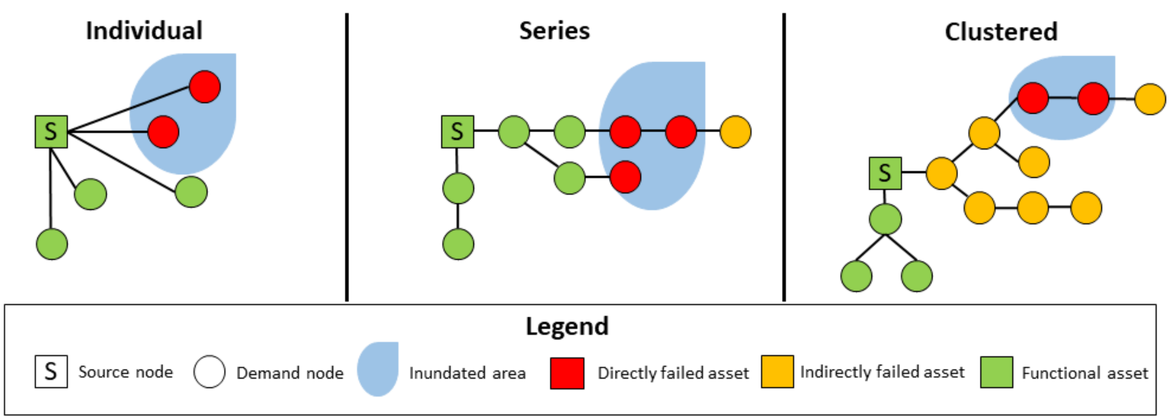

Fig. 2.4: Overview of different possibilities in the way demand nodes connect to a source, these differences influence the way direct failure in a demand node triggers cascade effects.

Direct failure memory

In case a temporal component is included in the model it is possible that water levels drop, leading to assets which have directly failed in a previous time step getting inundated below their critical water depth. In reality assets are likely to remain inoperative and will need to be manually reactivated or repaired. To ensure these assets do not become functional again in the model, the directly failed assets can be stored in memory. In this case these assets remain directly failed throughout the simulation. It is also possible to disregard this option in which case assets can become functional again if the water level at their location drops. It is never required to store indirect failure as this will always proceed in the same way from the direct failure.

Mitigation

In some networks mitigation operations can be applied as the flood event is ongoing. This mitigation can reduce failure as the flood event is still in development. Since this mechanism has to consider temporal flood parameters, modeling of mitigation is only possible if a temporal component is included in the model.

The exact method of mitigation will differ per network and location, so the possibilities for mitigation modeling need to be determined individually per network. However, for most situations mitigation can only reduce indirect failure. Actual repair of directly failed assets is outside of the temporal modeling scope. The mitigation method applied in this case study is described in paragraph 2.2.4. In general terms, three options for mitigation can be identified.

- Possible: A possibility for mitigation is available in this network. Assets which have failed indirectly can become functional again in later time steps.
- Indirect: Mitigation can not be directly applied in this network. However, through intersectoral interdependencies assets in another network returning to function can cause assets in this network to also become functional again.
- Impossible: No mitigation can be applied in this network. Any asset which fails will remain failed throughout the entire simulation.

2.1.5 Model results

The output of the model is a list of directly failed, indirectly failed and functional assets per network. Based on these failure types, model results are expressed in two fractions per network. These are the total percentage of failed assets (FA) and the share of indirect failure (IF). These values are calculated per network with equations 2.1 and 2.2.

$$FA = \frac{A_{df} + A_{if}}{A} * 100\% \tag{2.1}$$

$$IF = \frac{A_{if}}{A_{df} + A_{if}} * 100\% \tag{2.2}$$

In these equations the following parameters are used.

- A, the total number of assets

- A_{df}, the number of assets that fails directly
- A_{if}, the number of assets that fails indirectly

Alternatively, for networks in which the assets which fail are edges, these parameters can be weighted using length of failed edges. This gives a more appropriate indication of network functionality. In this case the same two values are calculated with equations 2.3 and 2.4.

$$FA = \frac{L_{df} + L_{if}}{L} * 100\% \tag{2.3}$$

$$IF = \frac{L_{if}}{L_{df} + L_{if}} * 100\% \tag{2.4}$$

In this case similar parameters are used.

- L, the total length of edges in the network
- L_{df}, the summed length of edges which fail directly
- L_{if}, the summed length of edges which fail indirectly

2.1.6 Technical implementation

Based on this modeling approach, a model can be created to simulate cascade failure in multiple networks that follows from a flood event. Because of the differences between infrastructure network failure behavior and the variations that exist in interdependency, every case study requires a creation of its own model. Furthermore, every included infrastructure networks requires its own scripts to simulate failure after flood events. However, the general structure of these scripts is always the same as shown in Fig. 2.2.

This study used a combination of Python and PostgreSQL to create the simulation model. While multiple programming approaches are possible to implement the general modeling structure, this approach will be the only considered option in this study. PostgreSQL is an object-relational database management system (Drake and Worsley, 2002). This is combined with the spatial extensions PostGIS and PGrouting which allow modeling of locational geometries and network analysis in SQL (Obe et al., 2017).

Data requirement and preparation

As stated the topology-based simulation approach has a relatively low data requirement. Topologies of infrastructure networks are sufficient to implement them in the modeling context. These topologies should contain both the locations of nodes and edges, in order to see how nodes are interconnected. Additionally, nodes should contain some indication whether they ought to be considered a source or demand node.

Before the simulation model is created all topologies are inserted into an SQL database as tables. These tables contain hexadecimal encodings of the geometries of nodes and edges which are used to see how nodes and edges intersect. Based on these geometries scripts are written to distinguish sub-networks. Demand nodes are linked to source nodes through a network graph analysis using the connections between them in the form of electrical cable, gas ducts or roads. Some manual corrections to the supplied data are required to ensure that all sub-network have one or more source nodes and that each demand node is connected to a sub-network. Assets that do not fulfill these conditions are either removed or data errors (e.g. snapping inaccuracies) that caused these nodes to be disconnected are identified and addressed.

Besides topologies of infrastructure networks some information on the flood event that triggers the initial failure is required. In case of an analysis without a temporal component this should be a single flood map containing maximum inundation depth. In case a temporal component is included, it should be a set of flood maps containing hourly inundations. In order to reference PostGIS geometries against these flood maps, they require to be in GeoTIFF raster format.

Simulation scripts

A Windows Batch script is created which calls a combination of Python and SQL scripts that carry out the failure simulation. The order in which the scripts for each network are called should depend on the inter-sectoral interdependencies. If failure simulation in a network is dependent on the results of another network, the simulation order should be chosen as such that these results can be provided.

The simulation of direct failure is done using a pre-existing Python script which references the encoded geometries in SQL tables to the flood event GeoTIFF. This Python script assigns an inundation depth to each asset. After this SQL scripts are used to compare the inundation depth to the asset critical water depth to see if direct failure occurs. After the direct failure assessment, an SQL script is called that checks whether assets which have a physical dependency on an asset of another network are still connected to this asset.

All assets which have failed directly or due to an inter-sectoral cascade effect are deleted from the SQL table. With the remaining assets an analysis is performed whether demand nodes are still connected to a source. This is done using Dijkstra's shortest path graph-algorithm with unweighted edges, as this was found to be the most time efficient simulation approach. This algorithm is part of the library of PGrouting. Due to the network characteristics described in paragraph 2.1.4 there are differences in the failure simulation scripts for different networks. Therefore, exact failure and mitigation processes have to be scripted separately for each network.

The duration of a simulation is mainly dependent on the amount of assets which can fail directly, as referencing asset geometries to the flood map is the most time consuming process in the model. For the five selected networks in this case study, total simulation time was approximately 45 seconds per time step. So a simulation including a temporal component for 48 hours took approximately 36 minutes.

2.2 Case study

Using the method described in the previous section, a model is constructed and tested for a case study. In the case study area five infrastructure networks are selected in which failure is simulated for different flood events. This section first describes the case study location and flood events, after which selected infrastructure networks are outlined.

2.2.1 Case study location and flood events

The Dutch region Zeeuws-Vlaanderen is selected as case study location to model cascade failure. The main consideration for selecting this region was availability of infrastructure data. Further advantages of Zeeuws-Vlaanderen are its manageable size and isolated nature due to the Schelde river and border with Belgium. Most infrastructure networks in Zeeuws-Vlaanderen obtain their commodity from the national net and most of the analyzed networks do not cross these geographical borders.

Flood event data for Zeeuws-Vlaanderen are provided through the Lizard Flooding portal by Nelen & Schuurmans. In this portal floods are modeled as a dike breach taking place during an outside water level with a certain recurrence probability. Depending on whether temporal aspects of a flood are taken into account different flood events are used.

Floods without temporal component

When no temporal aspects of a flood are taken into account, maps that contain maximum inundation depth of a flood event are used to analyze failure. A selection of four different flood events is made to simulate cascade failure at escalating disaster levels. All of these are modeled as simultaneous breaches at 5 locations in Zeeuws-Vlaanderen. Outside water levels for the different events have return periods of 400, 4000, 40000 and 400000 years. The latter of these events is used as the reference case, and shown in Fig. 2.5. Appendix A gives more information on selection of flood events and displays the inundation maps of escalating recurrence times.

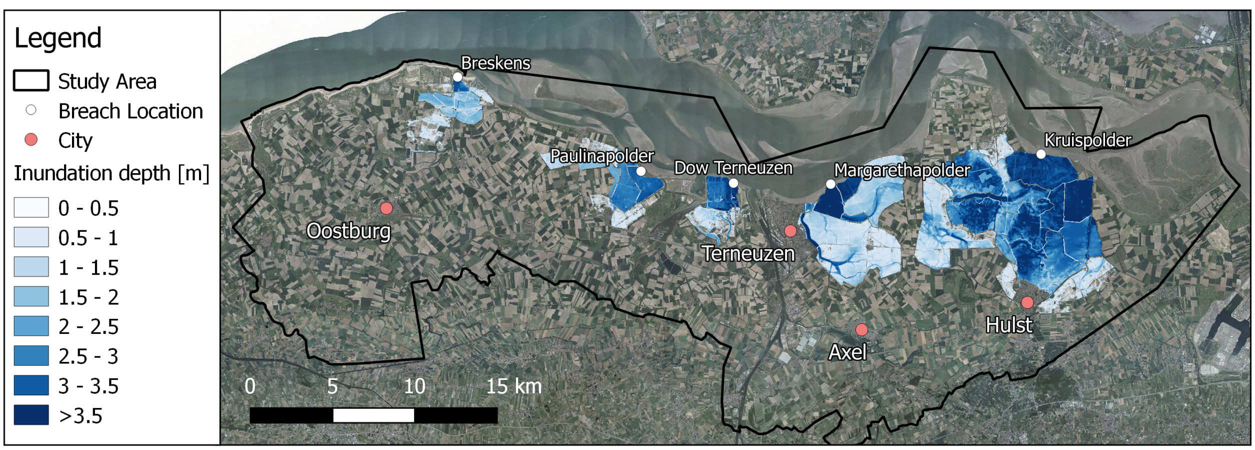

Fig. 2.5: Overview of case study location with the reference case flood event, multiple infrastructure networks are present within the study area but are not visualized in this figure.

The reason to model events as simultaneous breaches at five locations is to create incidents large enough to drive a level of initial failure required for cascade effects to occur. Nonetheless, due to their geographical properties Southern and Western areas of Zeeuws-Vlaanderen are less flood prone and are thus unaffected by initial failure. Disturbances in infrastructure in these areas can therefore only result from cascade effects.

Floods with a temporal component

When failure development over time is assessed, also the temporal parameters of a flood event are of importance. Instead of maximum depth, in this case maps contain inundation depth with a time step of one hour. When the model includes a temporal dimension, different flood events are used. These events follow from dike breaches at Breskens and the Kruispolder in the case study area, see Fig. 2.5. Similar to the non-temporal case these events have an average recurrence time of once in 400000 years. Fig. 2.6 shows the temporal progression of flood parameters for the selected events. While data on flood development is available for a period 144 hours after a breach, it is found the flood does not actively develop anymore after 48 hours so an event time of two days is selected. The Kruispolder flood event is significantly larger than the Breskens event both in inundated area and average inundation depth. However, the Breskens event inundates a more urban area with higher infrastructure density. Finally, flood development in the Kruispolder is slightly slower than in the Breskens event. Appendix A provides more information about selected flood events and gives an overview of what flood events are used for different modeling purposes.

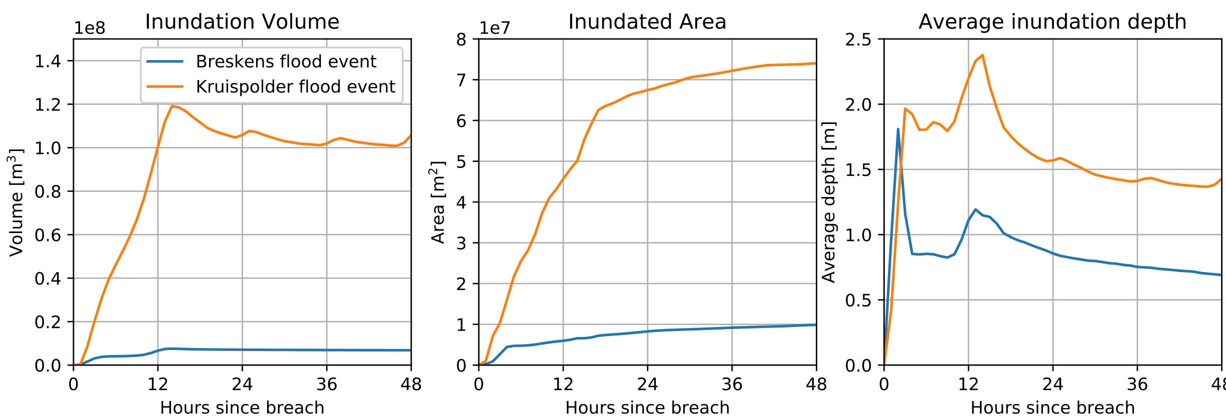

Fig. 2.6: Temporal progression of relevant flood parameters of floods used in model with temporal component.

2.2.2 Included networks

Five infrastructure networks in the case study area are selected to be used for failure simulation. These are the medium voltage, low voltage, telecoms, gas and transportation networks. This selection is based on what networks are most prone to cascade effects in literature (Van Eeten et al., 2011) and data availability. This section will describe included infrastructure networks, their failure behavior and how they are implemented into the model. Topologies of both electrical networks and the gas network are supplied by Enduris, the operator for these networks in the case study area. Topologies of the transportation and telecoms network are available as open data.

Medium voltage electrical network

The medium voltage network is part of the greater electrical network and used for the transmission of electrical energy from generation plants towards consumers. While some customers can be directly connected to the medium voltage network, its most common application is the transportation of energy towards transformer stations which turn medium voltage electricity into low voltage. Analogously, transportation over long distances is typically done in high voltage which is subsequently transformed into medium voltage electricity. The high voltage network is not included in this analysis because it has few assets in the case study area.

Source nodes in the medium voltage network are called main distribution stations, to avoid confusion with other assets in the electrical network these will be referred to as MV-stations. Herein, high voltage electrical energy usually enters via transmission towers as shown left in Fig. 2.7. In MV-stations electricity is transformed to medium voltage, after which it typically continues through underground power cable. Demand nodes in the medium voltage network are sometimes direct consumers, but most power flows to transformer stations which transform medium into low voltage electricity which is used by households.

In this analysis, the medium voltage network does not physically depend on any of the other selected networks. Its physical dependency on the high voltage network appears as a boundary condition, as this network is not included in the analysis. Failure can thus occur either directly from contact with water and as a result of intra-sectoral cascades. All assets in the medium voltage network have a measured height at which installations are mounted. This corresponds with a critical water level that would result in direct failure when reached, ranging from 62 to 115 cm.

There is a large discrepancy between source and demand nodes in the medium voltage network, as there are 8 source nodes and 1300 demand nodes. Due to the properties of electricity, demand nodes are only able to receive power from a single source. This gives medium voltage a sub-networks network structure as source nodes are not interconnected in normal configuration. Demand nodes are linked to their source in a series, as shown in Fig. 2.4.

A final consideration for medium voltage is a possibility for mitigation. This network contains cables which are inactive under normal conditions but can be switched on to restore power in

Fig. 2.7: Source and demand nodes of the combined electrical network. ***Left:*** *Source of electricity in the medium voltage network.* ***Right:*** *Destination of electricity in the low voltage network.*

indirectly failed assets. However, each node can only be powered through one route at a time because a node getting electricity from multiple sources leads to short-circuiting. Activation of redundant cables needs to be done manually through switches in network assets, which can be done during the flood event. Switching operations reconfigure the electrical network and are able to resupply electricity to indirectly failed nodes. Modeling of these mitigation operations is described in paragraph 2.2.4.

Low voltage electrical network

The low voltage network is the main distributor of electrical power to households and most other consumers. Transportation of low voltage electricity is almost exclusively done underground. Source nodes in the low voltage electrical network are transformer stations, which are the demand nodes in the medium voltage network. While the low voltage network delivers directly to consumers, this analysis will regard switch-boxes as shown on the right in Fig. 2.7 as demand nodes in this network. These switch-boxes are the last assets of the electrical network before connection to individual consumers. Data supplied by Enduris about the low voltage network also include connected customers counts per asset. However, it was chosen to regard failure at asset level and not to calculate the affected consumer numbers in order to keep consistency with other networks. Furthermore, the density of low voltage assets increases with population density as asset counts are far higher in urban areas. Therefore, asset failure should give a reasonable indication of affected population.

Low voltage assets also have a measured installation height which is selected as their critical water depth. For different types of assets this height ranges between 20 and 80 cm. Similarly to medium voltage, the low voltage network has a sub-networks structure as it is formed by many isolated sub-networks which are only connected through medium voltage. A difference with medium voltage is that there are more source than demand nodes in the low voltage network, creating some sub-networks which only consist of a single source node. Another difference is that demand nodes are connected to a source in a clustered structure, see Fig. 2.4. Indirect failure in the low voltage network can thus occur from two causes. Firstly through an inter-sectoral cascade when a transformer station loses access to medium voltage, causing all connected switch-boxes to lose power. Secondly, short-circuiting can lead to a cluster of demand nodes failing if one of them comes into contact with water.

Contrarily to medium voltage, cable redundancy in the low voltage electrical network is limited. Therefore operations to restore power will only be modeled in the medium voltage network. Nonetheless, indirect mitigation is possible in low voltage, as indirectly failed low voltage assets can return to power from mitigation in the medium voltage network.

Telecoms network

The telecoms network is used for all different forms of telecommunication. Huurdeman (2003) defines telecoms as "the transmission, emission or reception of signs, signals, writings, images and sounds; or intelligence of any nature by wire, radio, visual or other electromagnetic systems". Kotzanikolaou et al. (2013) mention telecoms as the most prominent network besides electricity for cascade failure occurrence.

The telecoms network is a collection of numerous networks with the function to provide transmission of information. In the case study area multiple of these networks are present. This study focuses on the subset of these networks that provides wireless communication, based on the topological data availability of assets in this network. Infrastructure assets of wireless communication networks are antennas, typically mounted on radio masts. A single mast usually carries multiple antennas providing different types of mobile communication and Internet for multiple providers. Antenna range varies based on the type of telecommunication they provide but more so on the amount and nature of obstacles around the mast. Therefore, radio mast density is far higher in urban areas than in rural areas. Besides radio masts, no other important telecoms assets are regarded. Since other infrastructure in the telecoms network is usually owned by a single provider, flooding of these assets does not result in absolute telecoms failure since other providers will still be operational. For this reason only radio masts are included as telecoms assets.

Because of the strongly variable range of radio masts it is not possible to regard failure in the telecoms network in a location based manner using only mast failure. Analogous to other networks asset failure counts are therefore used as the measure to express telecoms functionality. Since radio masts are the only included asset type, they are regarded as not interconnected meaning there are no intra-sectoral interdependencies in the telecoms network. All assets are considered to be source nodes in the analysis and failure in one radio mast does not trigger effects in other masts. This makes telecoms different from a typical network structure since assets are regarded to operate isolated from each other.

Radio masts can be affected by both direct and indirect failure. While antennas themselves are usually placed far too high to get inundated, radio mast installations are often placed at ground level. Based on discussion with the network operator an inundation depth of 50 centimeters is considered as the critical water depth which results in direct failure of a radio mast. Indirect failure in the telecoms network occurs due to a physical dependency on electricity, i.e. a mast is unable to operate if it loses power. Because exact connections between electricity and telecoms are unknown, it is assumed that radio masts lose power when the most nearby low voltage asset fails.

Gas network

For gas only the high pressure network is included in the model. Similar to medium voltage this is a trans-shipment network, transporting gas from the national net to the low pressure network. Source nodes in this network receive gas from the national net and demand nodes distribute this gas to the low pressure net (100 or 30 mbar). All gas network nodes are aboveground stations ranging in size from one to a couple of square meters.

In reality the gas infrastructure consists of two high pressure networks, one with a pressure of eight and one of four bar. Conversely to the electrical networks, their arrangement and operation is identical. Therefore, these networks are not considered separately within the analysis. This gives the gas network a mixed network structure, some source nodes are interconnected but in some locations gas is also provided by an isolated sub-network. Another difference with the electrical networks is that demand nodes in the gas network are considered to be linked individually to a source node. While in practice these connections can go through the same gas duct, failure in a gas demand node does never trigger effects in other gas assets. Therefore the gas network can be regarded as having individual demand node connections.

In Zeeuws-Vlaanderen the gas network is able to function autonomously without a requirement for electricity. This means that in the modeling context there are considered to be no interdependencies between the gas network and any of the other networks. Failure in the gas network is thus driven by direct failure and intra-sectoral cascade effects. A critical water depth of 75 cm is assumed for all gas assets, irregardless of node type. Indirect failure occurs in demand nodes if they are no longer connected to a functioning source.

Transportation Network

The primary means of transportation in Zeeuws-Vlaanderen is via the road network. Operation of this network differs from previous ones in that it is not node based, because assets are roads which connect numerous destinations. This means that in the transportation network assets that fail are considered edges. Furthermore, there are no clearly defined sources and demands in the transportation network.

In a flood disaster context a road segment is regarded as inaccessible and thus directly failed when a water depth of 20 cm is exceeded at any location on the road segment. However, also roads where this water depth is not reached can become inaccessible if all its means of access fail, causing indirect failure. In a modeling context a road is perceived as accessible when it can be reached from one of the main roads entering the study area. In the case of Zeeuws-Vlaanderen there are six provincial roads entering the area, thus defining six sources in the transportation network.

The transportation network has interconnected structure. Roads are considered to be connected in a series to the network sources as roads fail indirectly when they can not be reached, see Fig 2.3 and Fig. 2.4. Conversely to for example medium voltage however there is a lot of redundancy in the transportation network. Usually, far more than a single option is available to reach a destination. Therefore structure of the road network is fundamentally different.

The road network functions rather autonomously and is considered not to directly depend on other networks to operate. Some interdependencies that do exist concern traffic lights and operable infrastructures. Furthermore computerized control systems are used in transportation networks to influence traffic flows (Rinaldi et al., 2001). However, outages in these systems do not yield absolute failure in assets so they are not included in this analysis.

2.2.3 Study review

The interconnection between the five critical infrastructure networks is shown in Fig. 2.8. As depicted by the red arrows, assets in the low voltage network are directly dependent on medium voltage assets. The same goes for assets in the telecoms network being directly dependent on low voltage. Failure in the medium voltage network can thus trigger effects in the low voltage network which in turn can affect telecoms. The blue arrow indicates an informational interdependency. This describes the information requirement for mitigation operations in the medium voltage network. Maintenance crews are regarded as information which travels through the transportation network. This process is described in detail in paragraph 2.2.4. The medium voltage, gas and transportation network have no incoming physical dependencies, which means processes in these networks are limited to direct failure and intra-sectoral cascade effects. Conversely, the telecoms network has no intra-sectoral interdependencies, so all cascade effects in this network result from the dependency on low voltage electricity. Geospatial interdependencies are implicitly present in the model as they are accounted for in the assessment of direct failure.

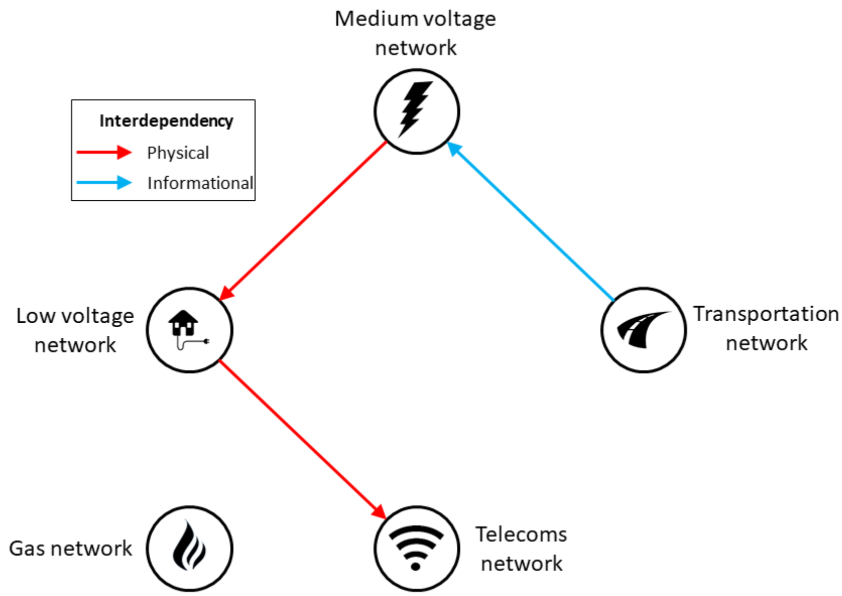

Fig. 2.8: Inter-sectoral interdependencies for selected networks in the case study area

Based on these interdependencies the modeling order of the infrastructure networks is chosen as follows:

1. Medium Voltage network
2. Low voltage network
3. Telecoms network
4. Gas network
5. Transportation network

In this way it is ensured that failure in provisionary networks is always known when inter-sectoral cascade effects need to be regarded. If mitigation is included, it is implemented as the final modeling step. Appendix B contains a flowchart detailing the order of failure simulation in the model over all selected networks in the case study.

The selected networks in the case study are different in structure and thus also in their failure behavior. Table 2.2 shows the network properties of selected infrastructure networks as described in paragraph 2.1.4. Furthermore, asset counts of networks after the data correction process are displayed in Table 2.3.

Table 2.2: *Network properties of selected infrastructure networks in the case study area.*

Network	Type of asset failure	Network structure	Demand node connection	Direct failure memory	Mitigation
Medium voltage	Nodes	Sub-networks	Series	Yes	Possible
Low voltage	Nodes	Sub-networks	Clustered	Yes	Indirect
Telecoms	Nodes	Not applicable	Not applicable	Yes	Indirect
Gas	Nodes	Mixed	Individual	Yes	Impossible
Transportation	Edges	Interconnected	Series	No	Impossible

Table 2.3: *Overview of source and demand nodes per modeled network in the case study area. NB: The 1219 source nodes in the low voltage network are also counted as demand nodes in the medium voltage network.*

Network	Source	Demand	**Total**
Medium Voltage	8	1300	1308
Low voltage	1219	1013	2232
Gas	17	113	130
Telecoms	99	0	99
Transportation	6	12256	12262

2.2.4 Mitigation modeling

Based on advice of network operators, only mitigation efforts in the medium voltage network are included in this study. However, these efforts can also lead to indirect mitigation in the low voltage and telecoms networks. Mitigation efforts are only modeled if a temporal component is included in the model.

Indirectly failed assets in the medium voltage network can become functional again by reconfiguration of the network structure. In the medium voltage network redundant electrical cable exists which does not transmit electricity under normal conditions. This cable can be activated which reconfigures the network and creates new connections between nodes, allowing assets which have failed indirectly to resume operation. Repair of directly failed assets is not included in the model as this process can only begin after the flood event has passed.

Restoration of indirectly failed assets is only possible if a node is connected to redundant cable. In the default situation 11% of the connections between two nodes is inactive. These connections can be activated by manually flipping a switch which can be located in either of the two assets that are linked by the connection. This introduces an interdependency between the transportation and medium voltage networks as no reconfiguration is possible if the appropriate asset can not be reached by road. As shown in Fig. 2.8 this is considered an informational interdependency as medium voltage assets rely on 'information' transmitted through the transportation network. Additionally, some assets do not require manual switching but can do so automatically if they receive a signal through the telecoms network. However, this is not done using the mobile communications network but uses the land line system. Furthermore, the amount of assets where automatic reconfiguration is possible is limited. Therefore only manual reactivation of redundant connections is taken into account.

Modeling of network reconfiguration is done every time step after the failure simulation. Every hour an analysis is performed whether there is redundant cable in the network which can be switched on in order to restore power in assets that are disconnected from their source node. If reconfiguration options exist it is regarded what switches need to be flipped and where these switches are located. Two conditions are required for flipping a switch to activate a connection. Firstly the asset where the switch is located must be accessible by road and secondly this asset can not be inundated at all, i.e. a water depth of one centimeter or less. These requirements are checked in the model and if they are both fulfilled the medium voltage network is reconfigured. The new network structure is then used in the next time step and power in reconnected assets is restored. Restoration of power is thus only possible in assets which have indirectly failed in a previous time step.

Accessibility of assets is a crucial criterion for network reconfiguration. Medium voltage assets are often built next to roads in which case this determination is straightforward, if the road is still functional the asset can still be reached. However, in some cases assets are located further away from roads or next to private roads which are not included in the transportation network. Furthermore, some medium voltage assets are located near multiple roads or road segments. In the model a simplification is used where an asset is considered accessible if there is a functional road within 10 meters. If no roads are present within 10 meters of an asset at all, it is considered accessible if the most nearby road still functions.

2.3 Sensitivity analysis

To regard the influence of uncertain variables on simulated cascade failures, a sensitivity analysis for key model parameters is performed. Based on the comparison of multiple sensitivity analysis methods for a comparable model by Ten Broeke et al. (2016) a one-factor-at-a-time (OFAT) routine is selected. Input parameters are set to a baseline value while values for one parameter at a time are altered. The effects on model output of these alterations are analyzed separately from each other. Unless otherwise stated, the sensitivity analysis is performed in a model without a temporal component.

The effects of changes in the input parameters are expressed in the previously described FA and IF fractions, see equations 2.1 and 2.2. A sensitivity analysis is performed for model input which can readily be parameterized. Included parameters in the sensitivity analysis are summarized in the next paragraphs.

2.3.1 Flood event size

Inundation of infrastructure assets drives direct failure which is the departure point of cascade effects. The four flood events described in paragraph 2.2.1 are used to analyze how increasing flood size influences infrastructure failure. More information about these flood events as well as inundation maps are supplied in Appendix A. These different flood sizes are used in separate model runs. Differences in resulting failure parameters indicate sensitivity for flood event size. The largest flood event, which is a combination of five floods with a recurrence time of 400000 years, is taken as the baseline value for this parameter in order to attain failure large enough for analysis in the reference scenario.

2.3.2 Asset critical water depth

Infrastructure assets do not directly fail when reached by a flood, but have some critical condition which leads to failure. Following the most common approach in flood damage assessment, inundation depth is taken as deciding factor (Jongman et al., 2014). A critical water depth is assigned to each asset in the various networks that when exceeded results in direct failure. For both electrical networks, the critical water depth is taken as the height of installations inside of the asset. For different types of assets present in the case study area this height is measured. For medium voltage this value ranges from 62 to 115 cm and for low voltage from 20 to 80 cm in different types of assets.

In the other networks no measured values were available to assign a critical water depth. In correspondence with the gas network operator, assets in the gas network are assigned a uniform critical depth of 0.75 m irregardless of asset type as a baseline. Telecoms assets are considered to fail when installations at the base of radio mast get inundated past 0.5 m. The transportation network uses a uniform inundation of 0.2 m at some point on the road to consider a road inaccessible in the base situation.

To analyze sensitivity for uncertainty in asset critical water depths, different values are used in model runs. Critical water depths are varied by multiplying their baseline values with a factor f for all assets in all networks simultaneously. Values for f range from 0.5 to 2 with a step size of 0.25.

2.3.3 Network reconfiguration potential

When a temporal component is included in the model, reconfiguration of the medium voltage network can decrease failure in both electrical and the telecoms networks. Potential reconfigurations are governed by the amount of inactive connections between nodes in the medium voltage network and the accessibility of these nodes. While this process is not suitable for parametrization it is possible to regard sensitivity for multiple options in this process. The Kruispolder and Breskens flood events, which include a temporal component, are used to analyze how different reconfiguration procedures influence power restoration. The following three options for network reconfiguration are compared.

- Normal reconfiguration: Reconfigurations are governed by two conditions; assets with switches that activate redundant connections must be accessible by road and completely uninundated. This is the base setting for network reconfiguration.
- No reconfiguration: No network reconfigurations are applied at all during the flood event. Inactive cable never gets activated and any node that fails remains failed throughout the simulation.
- Unrestricted Reconfiguration: The conditions that assets must be reachable by road and uninundated are ignored. Any medium voltage network reconfiguration that reactivates indirectly failed assets is applied.

2.4 Expert elicitation

Alongside the sensitivity analysis an expert elicitation process is employed which aims to achieve three objectives.

1. Determine influence of model premises
2. Assess model validity
3. Provide recommendations for model future application and improvement

To achieve these goals the interviews are structured around the model premises as described in paragraph 2.1.3. These premises introduce differences between the way failure is simulated and how it would occur in realistic flood events. The importance of these premises is discussed with the network experts to get an indication of how well the model is able to simulate failure behavior per network.

2.4.1 Expert selection

For both electrical, the gas and the telecoms network interviews are conducted with operator of these networks in the case study area. This is limited to one expert per network. Experts have broad knowledge about networks they work with, but little about other infrastructure in the case study area. Furthermore, experts do not have experience with flood modeling. Because only a single expert is consulted per network and experts are only able to comment on networks of their expertise, comparison between opinions of multiple experts per network is impossible.

For the transportation network no one with relevant expertise concerning the case study area was found available. Instead, an expert with experience in traffic modeling is consulted in the elicitation process to discuss model premises and simulation results. To keep consistency with other networks this is also limited to a single expert.

2.4.2 Elicitation process

Face-to-face interviews of approximately 45 minutes are held with the selected experts. Interviews are conducted separately from each other and only consider a single network per interview, i.e. experts are not asked to comment on problems in networks that are not their expertise. Because only a single expert is available per network, interviews are used to get a qualitative indication of model performance. A quantification of the uncertainty introduced by model premises would require aggregation of opinions of different experts (Warmink et al., 2011).

In advance of the interviews, an information package is sent to experts detailing the goal of the elicitation process and expectations of the interviews. This package also contained a concise description of the model procedure in which detail is given to the five model premises as this is the topic of focus in the interviews. Lastly it contained some simulation results which were custom-fit to the network of their expertise.

In the interviews, firstly all model premises are discussed separately from each other and the respective fault they introduce per network is reviewed. Experts are asked to comment on how suitable each premise is for their respective network and if they state that a premise introduces large inaccuracy, they are asked to suggest a more appropriate method to model failure. These suggestions are not for implementation into the model but can be used as leads for future model enhancement. Moreover, this question is used to ensure experts correctly understand the essence of model premises and their implications for failure simulation. When appropriate understanding of a premise is reached, the influence of a premise on model result inaccuracy is rated on a 3-point scale.

After all premises are discussed and rated separately, experts are asked to order premises from most to least influential for their network. Herein, influence describes whether a premise causes significant difference between simulated and realistic failure behavior. These orderings are used for comparison between the different networks. If a premise is consistently ranked as being among the most influential, this could be a departure point for introducing more network-specific behavior to the analysis of failure in critical infrastructure. Conversely, if a premise is repeatedly considered among the least influential it will not have the highest priority for improvement in a more complex analysis.

Finally experts are asked to judge how well the current model is able to simulate failure in the network of their expertise, taking into account the previously discussed differences between simulated and realistic failure caused by the model premises. Again this is done qualitatively, i.e. experts are not asked to estimate what fraction of failure is simulated correctly. Instead the aim is to provide an interpretation of whether simulated failure behavior is akin to realistic failure patterns. Here experts are also asked to comment on differences between simulation results and failure behavior they would expect. If possible, potential reasons for these differences are also discussed. This last question does not only have the intention to assess accuracy of simulation results in the case study area but also tries to get insight in how well the same or similar networks can be modeled at other locations to assess generic applicability of the model.

2.4.3 Bias minimization

Because only the opinion of a single expert per network is used to assess model performance, it is particularly important to be observant of bias these experts might possess. Van der Sluijs et al. (2004) list sources of bias typically encountered in expert elicitation processes. Because experts are only asked for a qualitative assessment some of these regularly encountered bias sources are unlikely to be met in this process. The most likely biases that might be prevalent in this process are availability and motivational bias.

Availability bias refers to the tendency to give too much weight to readily available data or recent experience, while this data might not be representative of the situation under discussion (Van der Sluijs et al., 2004). In this process experts might refer to past disruptions in their networks to analyze the role of model premises. While such approaches are not necessarily incorrect, it is important to consider that these outages will have other causes than a flood event and might therefore display fundamentally different failure patterns.

Motivational bias occurs when the response of an expert is influenced by factors such as moral or professional responsibility, legal liability or peer credibility (Knol et al., 2010). A cause of motivational bias in this study might be unwillingness to admit vulnerability to flood events. Furthermore experts might hold back criticism to the model in an attempt not to discredit the efforts that have gone into its creation.

To minimize bias in expert response, the goal of the elicitation process is explicitly stated when the interviews are arranged, in the preceding information package and at the start of the interviews. This should incline them to provide all valid criticism on the model. In accordance with Knol et al. (2010) experts are also asked to provide detailed argumentation for all given judgments. Nonetheless, bias is likely to be present in expert response, therefore their answers are thoroughly analyzed and potentially biased comments are weighted appropriately.

3 | Modeling results

Infrastructure failure is simulated using multiple flood conditions in the case study area. This chapter provides results of model runs for both the non-temporal and temporal modeling approach. Lastly, also results of the sensitivity analysis are provided.

3.1 Reference case

Cascade failure is simulated for the reference case, not taking in account temporal flood aspects. This reference case has the parameters listed in section 2.3 set to their described base values. In this reference case 14.2% of the study area has been flooded. Failure counts per network for this scenario are shown in Table 3.1.

Table 3.1: Failure per infrastructure network in the reference scenario. Absolute values are expressed as asset counts except for the transportation network where failure values are expressed in road kilometers.

Network	**Asset counts**				**Failure parameters**	
	Direct	Indirect	Functional	Total	FA	IF
Medium voltage	101	110	1097	1308	16.1%	52.1%
Low voltage	224	121	1887	2232	15.4%	35.1%
Telecoms	11	7	81	99	18.2%	38.9%
Gas	15	6	109	130	16.2%	28.6%
Transportation (km)	367	32	2210	2609	15.3%	8.0%

3.1.1 Medium voltage network

In the medium voltage network 16.1% of assets stop functioning under chosen conditions, with indirect failure being slightly more prevalent than direct failure. Fig. 3.1 shows outages being relatively confined to the flooded area with only a few assets failing outside of inundated locations. A notable effect is that a moderate share of assets inside of the inundated area do not fail directly, as water levels do not reach their critical water depth. However, almost all of these assets lose their functionality indirectly still leading to almost complete power loss within inundated areas. One of the eight MV-stations in the study area gets flooded up to the point of direct failure. However, only 17 demand nodes connect to this station, so effects of the flooding of this source node are limited.

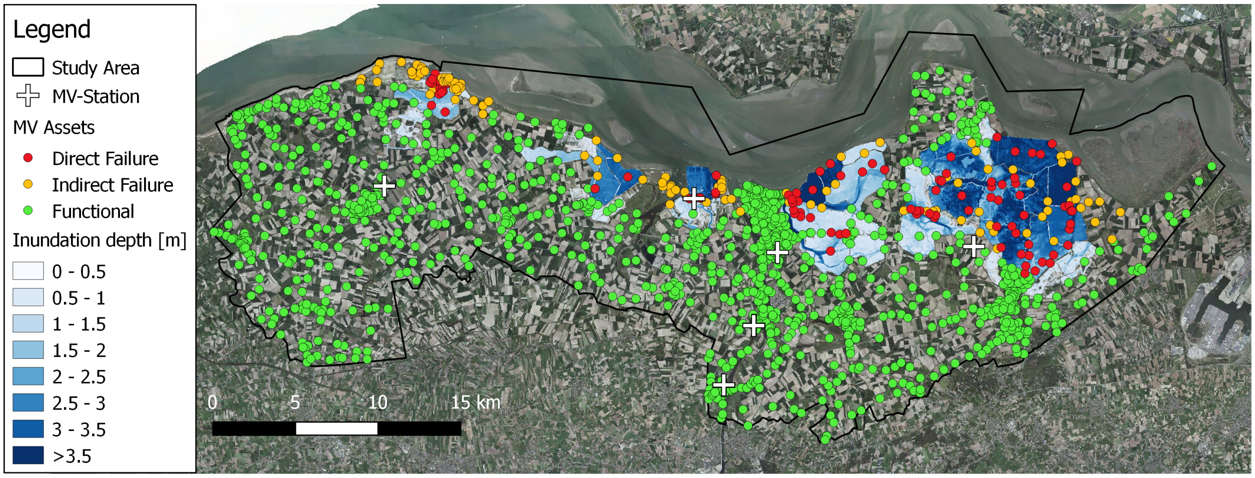

Fig. 3.1: Failure of assets in the medium voltage electrical network in the reference scenario.

3.1.2 Low voltage network

The low voltage network displays very similar failure behavior to medium voltage. As shown in Fig. 3.2, effect locations coincide with those in medium voltage and also total asset failure (15.4%) is similar. However, while indirect failure is more dominant in the medium voltage network, the low voltage is more influenced by direct failure.

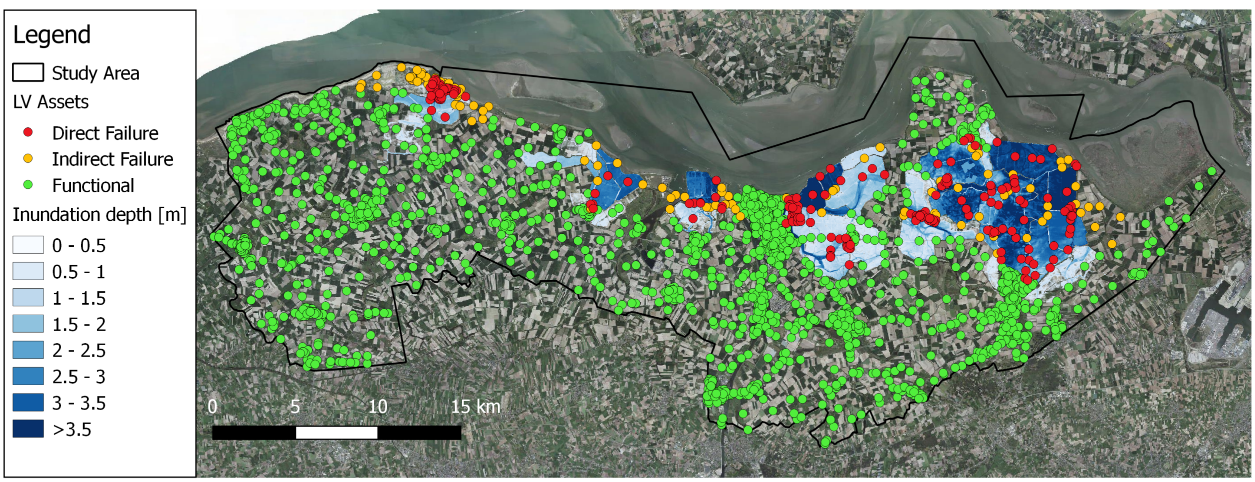

Fig. 3.2: Failure of assets in the low voltage electrical network in the reference scenario.

3.1.3 Telecoms network

The telecoms network displays the highest FA value of all selected networks in the case study area in the reference scenario. However, the value of 18.2% does not significantly differ from FA-values in other networks. Based on the spatial distribution of failed radio masts in Fig. 3.3, it seems likely that access to mobile communications will be disrupted in and around the inundated area. However, similar to the electrical network disruptions are unlikely to occur more distant from the flood event as radio towers outside the affected area mostly remain operative.

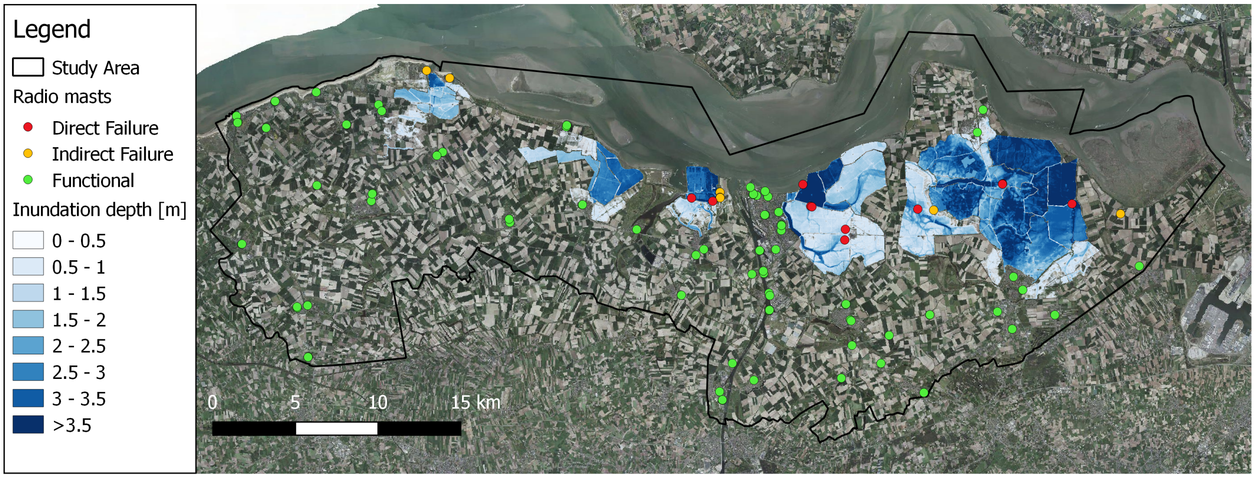

Fig. 3.3: Failure of assets in the telecoms network in the reference scenario.

3.1.4 Gas network

Compared to the previous networks, asset failure in the gas network is similar at 16.2% but the share of indirect failure is notably lower as only 6 assets fail indirectly. As shown in Fig. 3.4 this indirect failure all occurs around the same location as a result of a source node directly failing. It should be noted that the gas and telecoms networks have far fewer assets than the electrical networks which influences failure percentages.

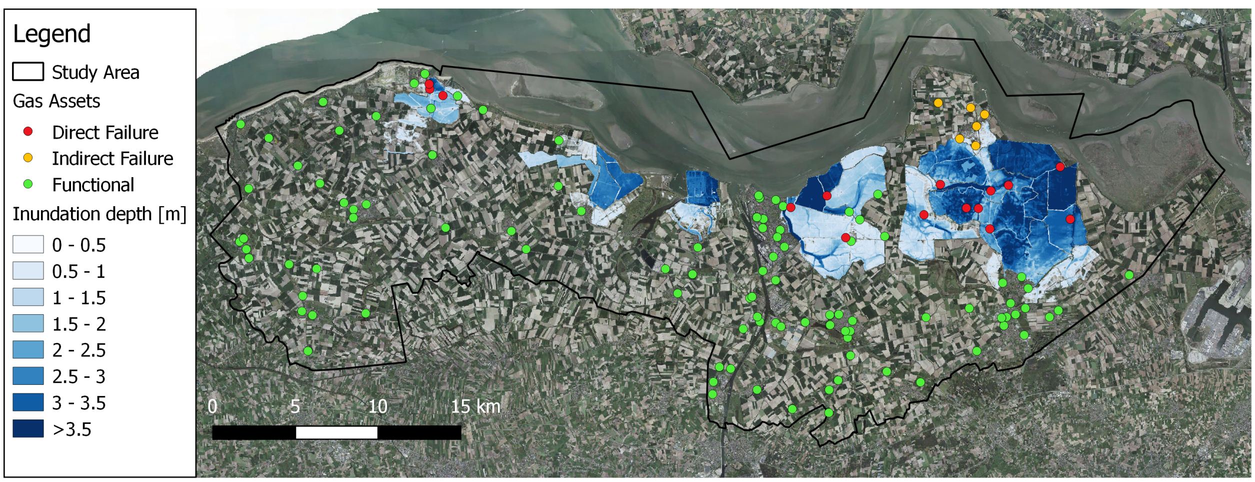

Fig. 3.4: Failure of assets in the gas network in the reference scenario.

3.1.5 Transportation network

Asset failure, expressed in road kilometers, under standard conditions has a value similar to the other networks (15.3%). However, the transportation network is almost completely dominated by direct failure. As visible in Fig. 3.5 indirect failure almost exclusively occurs on roads inside the flooded area where a critical depth is not reached on the road itself.

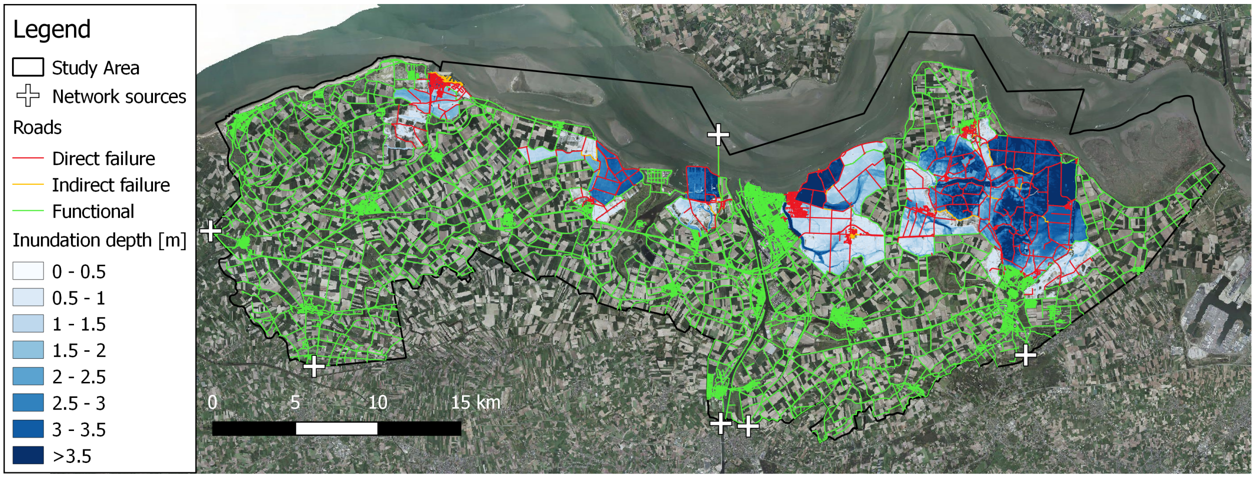

Fig. 3.5: Failure of roads in the transportation network in the reference scenario.

3.2 Progression during flood event

With a temporal component introduced to the model, development of failure as a flood event is ongoing can be regarded. Flood events following from breaches at Breskens and the Kruispolder with an outside water level with an average recurrence time of 400000 years are selected for analysis of cascade effects. Description of these flood events and progression over time of relevant flood parameters are provided in Appendix A.

3.2.1 Breskens

The failure in infrastructure networks following from this flood event is shown in Fig. 3.6. Despite using a flood event which inundates a relatively small part of the study area, the FA values are calculated over the entire case study area, as to not add additional spatial scales.

Interestingly, the highest FA-values for the medium and low voltage networks are reached two hours after flood event onset, at 3.8 and 4.1% respectively. Both networks also display a peak value in indirect failure at this time, indicating that assets being inundated early in the flood event are a trigger for cascade effects. After this initial failure, network reconfiguration in the medium voltage network reactivates nodes resulting in permanent power restoration.

Development in total asset failure almost completely halts after ten hours into the flood event, with only the FA-value for the transportation network slightly increasing after this point. This phenomenon is odd since inundated area of the flood events and average inundation depth over the flooded area are still increasing at this point, as shown in Fig. 2.6. However, the IF-value of the electrical networks decreases until 16 hours into the flood event. This signals assets first failing indirectly and then directly as the water level surpasses their critical inundation depth.

The gas network is not subject to cascade effects in this flood scenario, with only 3 assets directly failing triggering no indirect failure as no source nodes fail. Conversely, for the telecoms network only indirect failure occurs as two radio masts lose power two hours after the dike breach but none are directly affected by the flood event. The transportation network displays some indirect failure in this event but similarly to the model without a temporal component direct failure is far more prominent in this network.

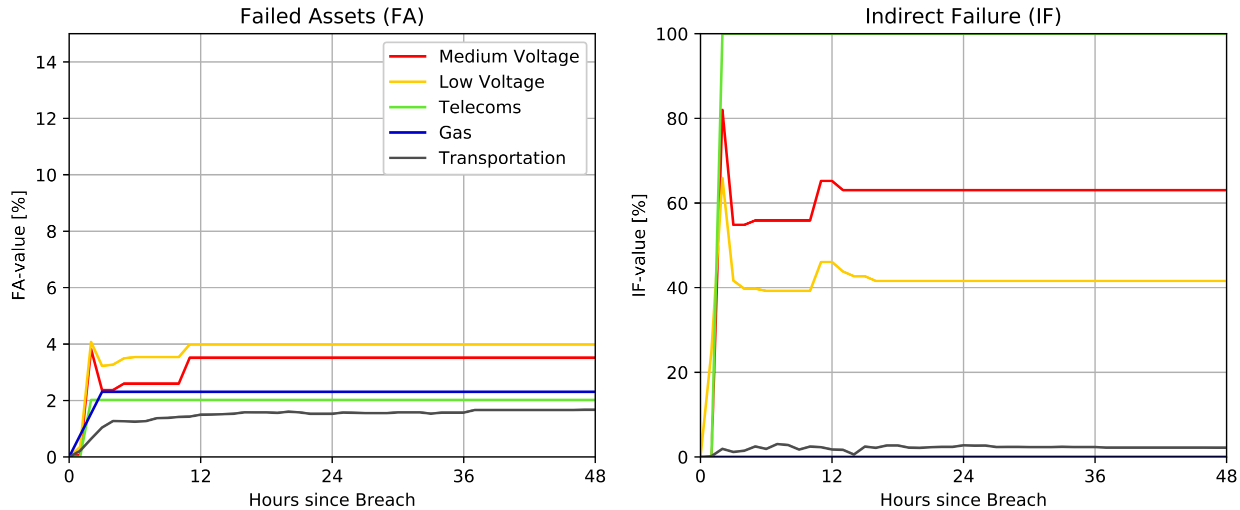

Fig. 3.6: Progression of failure parameters over time after the Breskens flood event.

3.2.2 Kruispolder

While having the same recurrence time, the Kruispolder flood events inundates a notably larger area and yields higher water depths than the Breskens flood event. This is reflected by the progression of failure parameters shown in Fig. 3.7. Figures detailing failure for this flood event in the medium voltage and gas networks at 5, 10 and 15 hours after the dike breach are included in Appendix C.

Flood development in this scenario is slower than in the Breskens flood event, with notable changes in failure parameters happening up to 30 hours after the dike breach. Even in the last hour failure in a medium voltage asset triggers an additional cascade as the inundation depth at this location increases by 1 cm, just past the stations critical water depth. This in turn triggers

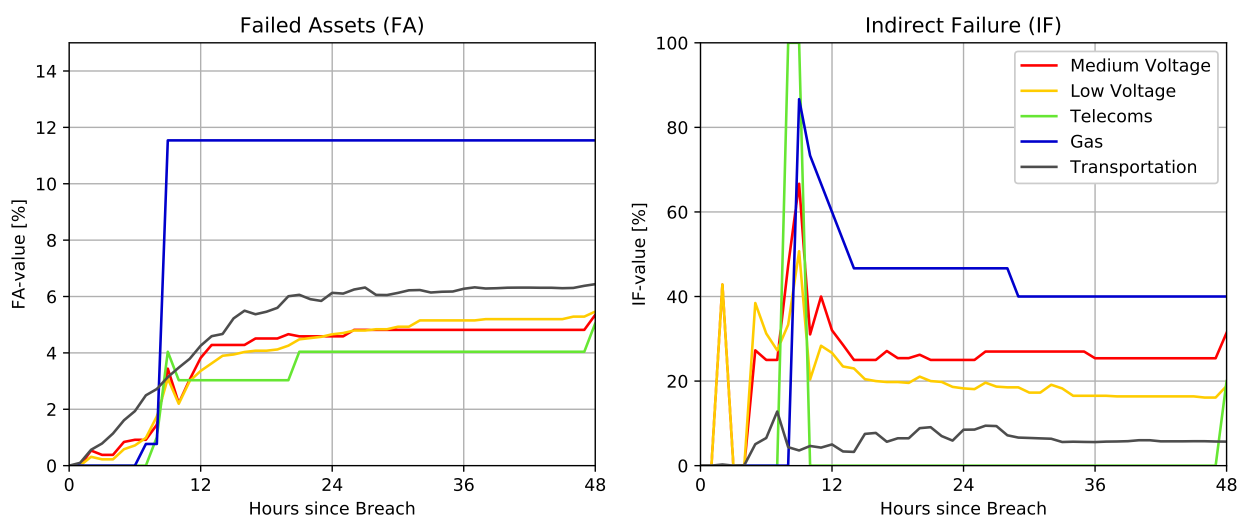

Fig. 3.7: Progression of failure parameters over time after the Kruispolder flood event.

effects in the low voltage and telecoms networks. Large fluctuations of the IF values for both electrical networks are caused by network reconfiguration happening during flood development. Herein occasionally assets get restored to power only to fail again a few time steps later.

This effect is also notable in the telecoms network, where in a single time step the asset failure goes from completely dominated by indirect failure (IF-value of 100%) to completely dominated by direct failure (IF-value of 0%). This is caused by reconfiguration in the medium voltage network returning power to indirectly failed assets but in the same time step development of the flood event causes radio masts to get inundated past their critical depth.

A strong difference with the Breskens scenario is shown in the gas network where failure of a source node nine hours after the initiation of the flood triggers a large cascade, also represented by the peak in the IF-value at this time. Afterwards, a decrease in the IF-value is witnessed while the FA-value remains constant, indicating direct failure occurring in nodes which had already failed indirectly. Figures displaying this effect are included in Appendix C.

3.3 Sensitivity analysis

A sensitivity analysis using OFAT methodology is performed for the parameters mentioned in section 2.3. This section shows the influence of changes in these parameters on the Failed Assets (FA) and Indirect Failure (IF) fractions, as described in paragraph 2.1.5.

3.3.1 Flood event size

The influence on simulated cascade failure of the flood event size represented as the recurrence time of the individual dike breaches is shown in Fig. 3.8. Herein the model without a temporal component is used, which also means no network reconfiguration is applied.

As expected asset failure increases with flood event size. When FA-values are compared to the percentage of inundated land as provided in Appendix A, asset failure counts are usually slightly higher than the flood extent. This corresponds with the observation that most assets

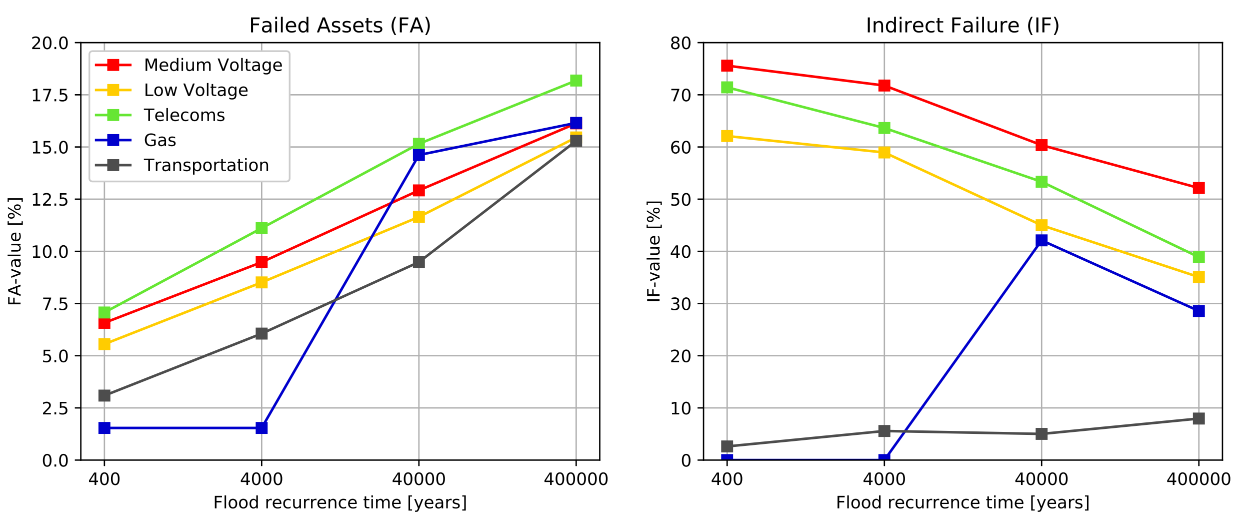

Fig. 3.8: Influence of size of flood event on failure parameters for different networks in Zeeuws-Vlaanderen.

within inundated areas fail, with occasional occurrences of indirect failure nearby these flooded areas. For most networks growth in asset failure is quite gradual with increasing flood size. For the gas network however a large discrepancy exists between flood recurrence times of 4000 and 40000 years. This is caused by a source node directly failing at larger flood sizes, leading to multiple demand nodes losing access as also visible in Fig. 3.4. A further observation is similarity in FA-values for different networks at the largest flood, while they are more spread for smaller floods.

For the share of indirect failure the sectors display varying behavior. For both electrical and the telecoms networks this value decreases with flood size while the opposite effect is observed in the transportation network. For the gas network no clear trend is visible because of the aforementioned reason. In general larger flood events seem to result in less indirect failure.

3.3.2 Asset critical water depth

The influence of changes in the asset critical water depth are shown per sector in Fig. 3.9. Changes of up to a factor 2 in the asset critical water depth result in a smaller difference in asset failure than flood event size does. The largest fluctuation is seen in the medium voltage network where increasing installation height with a factor 2 would reduce asset failure in the reference scenario from 18.5% to 12.5%. The smallest change is observed in the transportation network. This is attributed to the fact that many roads in the inundated area are located on dikes in which case they do not get flooded. Roads not located on a dike are typically inundated far beyond their critical depth so variations in this critical depth have little effect.

Another notable effect is that the share of indirect failure increases with critical depths for the gas and medium voltage network while it stays relatively stable for low voltage and transportation. This indicates that some assets in the gas and medium voltage network do not fail directly due to their increased critical water depth but still lost their function from indirect failure. For low voltage and telecoms assets this effect is not observed, possibly because asset critical water depths in these networks are generally lower so variations in these values have a smaller impact.

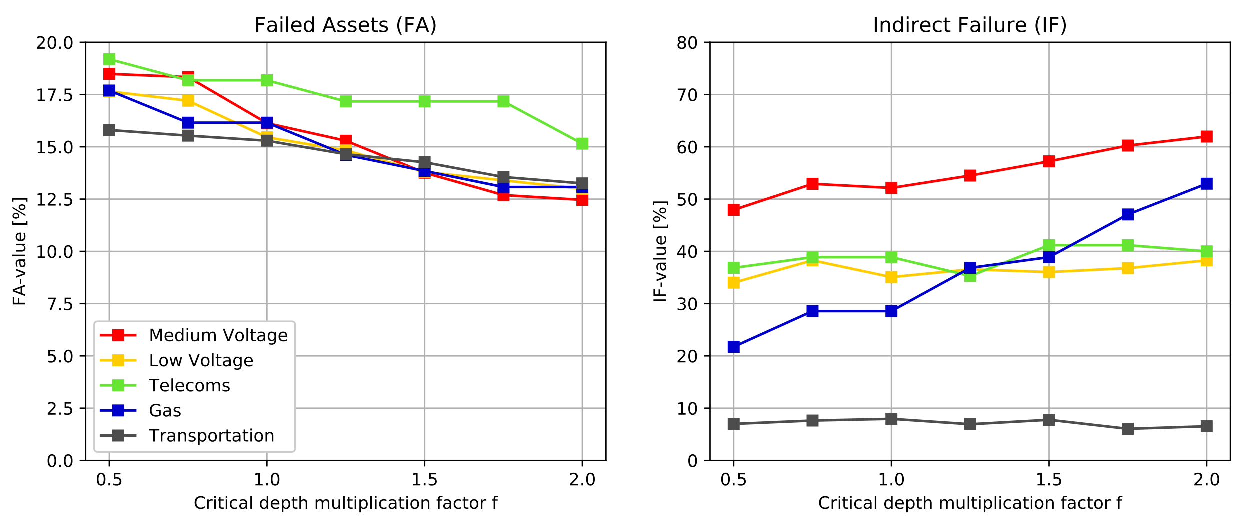

Fig. 3.9: Influence of changes in the asset critical water depth for different networks in Zeeuws-Vlaanderen. Reference case asset critical depths are multiplied with a factor f ranging from 0.5 to 2.

3.3.3 Network reconfiguration potential

Sensitivity for the network reconfiguration potential is measured using the model including a temporal component. Conversely to the previous figures, Fig. 3.10 therefore shows the progression of FA and IF values over time in the medium voltage network. For this figure the Kruispolder flood event is used for failure simulation. Additional figures showing effects of reconfiguration settings on the low voltage and telecoms networks and for the Breskens flood event are provided in Appendix D.

Network reconfiguration leads to significant reduction in asset failure for this flood event, as 15 medium voltage assets are functional under normal reconfiguration which fail when no reconfiguration is applied. This corresponds to a 18% reduction in total medium voltage failure, and a 41% reduction in assets which fail indirectly in this network. For the Breskens event similar reductions of failure are achieved through network reconfiguration. For both cases this difference is achieved in the early stages of the flood event, after which point it remains relatively constant.

Due to the strong coupling between medium and low voltage, the low voltage network displays very similar behavior. For the Kruispolder flood event the total reduction in asset failure at the end of the simulation is 12%. For the Breskens flood event this value is 10%. In the Kruispolder flood event power restoration in the low voltage network in turn drives the reactivation of a single radio mast. In the Breskens flood event medium voltage network reconfiguration does not influence functionality of telecoms assets.

The difference between normal and unrestricted reconfiguration is negligible. In Fig. 3.10 lines for these reconfiguration options almost completely coincide. The same effect is observed for the low voltage and telecoms networks as well as for the Breskens flood event. The requirements that assets must be accessible by road and uninundated for normal reconfiguration do not restrict potential reconfigurations under these conditions.

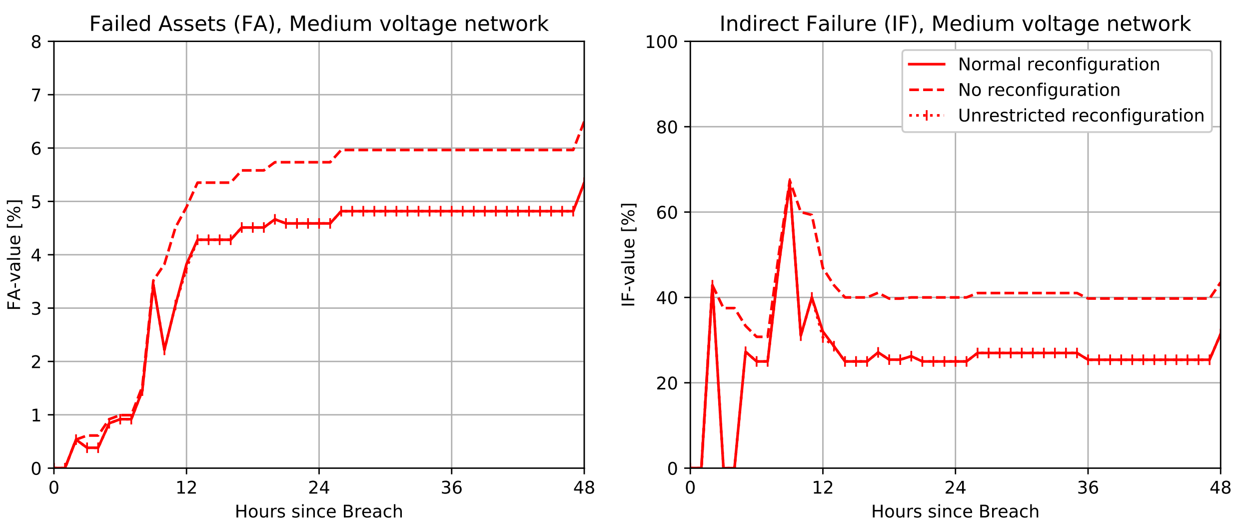

Fig. 3.10: Influence of different reconfiguration options on the progression of FA and IF values following from the Kruispolder flood event.

4 | Expert elicitation

Expert elicitation is performed in an interview setting. Herein, infrastructure networks are discussed separately with a single expert except medium and low voltage which are discussed simultaneously. While the low voltage network is simpler in structure, it is stated that for the current modeling context no differences between low and medium voltage need to be taken into account. Therefore these networks are combined in the elicitation process. Firstly the interview process and encountered biases are summarized. Secondly, influence of model premises and premise rankings as given by the experts are discussed. Lastly, additional observations about failure processes mentioned by experts are provided.

4.1 Expert response and bias

Interviews spanned between 30 and 60 minutes and all followed the same structure. Preparedness of experts for the interviews varied, resulting in different levels of model understanding at interview onset. Through discussion experts reached sufficient understanding of model premises to supply meaningful contributions to the study.

Some availability bias was encountered in the interviews. Experts occasionally refer to past failures in their network to indicate influence of cascade effects. These past failures are unrelated to flood events or other natural hazards, so how these situations translate to a flood context is unclear. Motivational bias is mainly encountered as experts being inclined to focus on normal network operation, which is typically more their expertise. The role of motivational bias in the elicitation process is likely limited however, as experts are generally able to provide structured reasoning for arguments and do not seem hesitant to admit network vulnerability.

A notable source of error in the interviews is experts confusing model premises with sources of uncertainty. For example, while experts state inundation depth is suitable as being the only consideration for node failure, they rate this premise as influential due to uncertainty in the value of node critical depths. The scope limitation premise is also consistently ranked as highly influential, which in some cases can be attributed due to uncertainty in for example impact of flood events in higher order networks. Scope limitation was also frequently regarded as a bin premise, with experts attributing network-specific failure processes to influence of this premise. Even though premises were sometimes misinterpreted they are left unaltered to keep consistency between the interviews.

4.2 Model premise influence

Model premises that were discussed with experts are displayed in Table 4.1, this table summarizes the premises that were defined in paragraph 2.1.3.

Table 4.1: Overview of model premises discussed in the expert elicitation process

ID	Name	Short description
1.	Only selected asset failure	Only the failure of selected assets is considered in the analysis. All other infrastructure which can play a role in network failure such as underground cable is ignored.
2.	Depth as only fail criterion	Inundation depth of a node is the only factor that drives direct failure. Other flood related parameters do not influence failure.
3.	Binary failure	An asset either has full functionality or completely failed. The model is unable to account for diminished functioning of assets.
4.	No flow simulation	There is no simulation of flow over the network, only a connection to a source node is required for functioning. Production capacity of source nodes and transportation capacity of network edges are ignored.
5.	Scope limitation	Only described processes can influence network failure. Incidents that occur in other networks or outside case study boundaries can not influence cascade effects within the case study area.

Based on expert response premises in this table are rated on a 3-point scale. Table 4.2 summarizes the influence assigned to individual premises per network. The three scores defined in this scale are:

L Large: The model premise is clearly influential on model results and causes a notable difference between simulated and realistic failure behavior

M Medium: There is a modest influence of the premise which might cause simulated failure behavior to slightly deviate from reality

S Small: Influence of the premise on model results is negligible and it will not lead to discrepancies with realistic failure

Table 4.2: Influence of model premises per network. Model premises correspond to IDs in Table 4.1

Network	**Model premises**				
	1.	2.	3.	4.	5.
Electricity	M	S	S	L	L
Telecoms	M	S	S	L	M
Gas	M	M	S	L	S
Transportation	S	S	M	L	M

Experts usually consider inundation of aboveground assets as the main cause of direct failure. For the electrical, telecoms and gas network experts also mention failure of underground infrastructure as a potential cause for cascade effects but this is generally rated as being far less vulnerable to flooding. Within these assets inundation depth is considered as being a good single indicator of failure. Except for the gas network assets fail as soon as they get inundated, so additional flow parameters will be of lesser importance. For the gas network also duration and flow velocity could be considered as additional failure indicators.

Binary failure of nodes is also encountered in realistic failure patterns. Any assets involving electricity either function normally or completely fail due to short-circuiting. In the gas network automatic safety measures in assets will completely shut down asset functionality in case it becomes unable to properly function. The expert for the transportation network mentions that single roads can be considered in a binary manner but in the case of larger areas this is inaccurate, especially in case of indirect failure occurring in larger areas.

The absence of flow simulation in the model is consistently considered as causing large differences between realistic and simulated failure patterns. In reality limited production capacity of source nodes will make them mostly unable to replace each other in case one of them fails. Other effects mentioned are that gas and electricity can only travel a limited distance from start to destination and that network structure can make it impossible for source nodes to carry over each others function even if enough capacity were available. Experts for the electrical and gas network mention that depending on certain circumstances effect of failed source nodes could be partially mitigated. This would however require location-specific knowledge to determine. The transportation and telecoms networks have less clearly defined source nodes. However, for these networks the peak in demand that occurs with a crisis situation is mentioned as an important cause of network failure which currently cannot be assessed due to the inability to simulate network flow.

The influence of the scope limitation in this study strongly varies per network. This is mostly due to different influences of higher order networks as no interdependencies with other networks are considered to be a source of failure. The high voltage network is mentioned as having some assets, even within the case study area, where flooding would cause almost complete electrical outage. A similar effect is possible for telecoms, however these assets all have at least one backup which can take over in case of a single failure.

Subsequently, experts were asked to order premises from most to least influential for the simulation of failure behavior in their network. In this context most influential means that a model premise has the largest contribution to differences between model results and realistic failure patterns. Orderings provided by the experts are shown Table 4.3

Table 4.3: Orderings of model premises from most to least influential. Numbers in the table correspond to IDs in Table 4.1 and are ordered from most influential for failure simulation (left) to least influential (right)

Network	Most influential $\Longleftrightarrow$ Least influential				
Electricity	5	4	2	1	3
Telecoms	4	5	1/2	1/2	3
Gas	4	5	1/2	1/2	3
Transportation	5	4	3	1	2

There is some disconnect between Table 4.2 and Table 4.3. These differences arise due to experts including other factors in their rankings, e.g. uncertainty about premises or what factors they think would be easier to eliminate. Nonetheless, a consistently observed finding is that premises which mostly concern direct failure are considered less influential than premises that relate more to cascade effects.

4.3 Additional observations

While interviews mostly focused on predefined model premises, experts also mentioned other effects that would occur in infrastructure networks in case of a flood event. These effects are usually network-specific failure behavior that currently is not accounted for in the analysis.

Experts for the transportation and telecoms network mention a possible increase in demand not only during the flood event but also in advance of the flood. This study considers infrastructure contact with water as the chronological departure point for network failure, but experts in the transportation and telecoms mention that the most detrimental network failure can happen in advance of the flood. Especially if areas are being evacuated, failure during the event will be of lesser significance than effects before the flood onset.

Similarly, experts mention long-term effects of floods. After a flood event has passed and network functionality has returned this will likely make assets more vulnerable to failure. For these effects flood parameters other than inundation depth, such as inundation duration and salinity, can become more influential.

Another observation made regarding transportation is the multiple functions of this network. In the applied context only accessibility is regarded for which the expert states a realistic view is provided. However, areas which might still be accessible for basic needs can still have completely lost access to the socioeconomic function of the transportation network. The telecoms network also has more than a single function and moreover radio masts carry service for multiple providers. While the current methodology is able to accurately assess whether radio masts are functional, it is unable to locationally determine access to the telecoms network.

Lastly, experts state that in most cases the applied methodology is also suitable for the same networks in other study areas. Also in more urban areas the nature of infrastructure networks does not differ in such a way that a different approach is required. For telecoms however a higher asset density makes it more difficult to assess telecoms functionality in a location based manner. However, in this and all other considered networks it is stated that failure patterns resulting from flood events will likely happen in a similar manner as in this case study.

5 | Discussion

This chapter discusses results of this study in a twofold division. The first section reviews application of the created model in the case study and aims to interpret results found within the study area. Subsequently, findings of the case study and expert elicitation process are used to analyze model performance and application beyond the current case study.

5.1 Case study results

Failure in five infrastructure networks in the Zeeuws-Vlaanderen region has been simulated in order to see to what extent cascade effects can be simulated. Failure is expressed at the level of infrastructure assets which details network functionality to town or street level. However, in some cases it is uncertain how asset failure corresponds to location based loss of service. For example, in the telecoms network it is unclear how radio mast failure corresponds to cell phone reception. This study only aims to determine asset failure in order to test the model, without analysis how customers are affected by network outage.

5.1.1 Cascade failure occurrence

Under reference case conditions all networks except medium voltage have a higher share of direct than indirect failure. In other scenarios indirect failure can become more prevalent in certain networks but direct failure typically remains dominant, especially when mitigation is taken into account. This means the largest share of outage is caused by infrastructure assets being damaged by water, and not as a result of cascade effects.

The transportation network is continually observed as being hardly affected by cascade failure. This is partly caused by the modeling methodology as the expert states that some functions of the transportation network are likely to be disrupted in case of a flood event. However, the low vulnerability for cascade effects is also a result of the large redundancy in this network. Due to the interconnected network structure, locations are typically accessible through a large number of different paths which makes failure of a few of them less problematic. Other networks typically have less inherent redundancy, for example the electrical and gas networks which have a sub-networks or mixed network structure. This means in many cases, only a single source supplies a demand. Any failure in either this source or in other assets which are part of the route to the demand node therefore causes a cascade effect, greatly increasing possible consequences of a single asset failure in these networks.

5.1.2 Inter-sectoral effects

Infrastructure interdependencies are classified as existing within a single network (intra-sectoral) or between different networks (inter-sectoral). With the network selection applied in this case study, the role of the former in cascade failure occurrence is strongly dominant over the latter. Three out of the five selected networks do not have a physical dependency on another network within the chosen modeling scope. Furthermore, it can be argued that the medium and low voltage networks form a single network making telecoms the only network with an incoming physical dependency.

Nonetheless, experts do not mention other networks or missing interdependencies between the currently selected networks which would lead to additional inter-sectoral cascade effects. However, a clear identified improvement for this analysis would be to include the dependency of selected networks on networks of higher order, such as the high voltage or national gas network. Failure high up in a network hierarchy could completely shut down certain networks, substantially exceeding failure extents encountered in this study. Such an occurrence would usually require some asset failure outside of the case study area. Only for electricity the higher order network has assets within the case study area where flooding would trigger substantial power outage.

Another reason for the limited impact of inter-sectoral effects is the absence of circular interdependency between selected networks. As shown in Fig. 2.8 the inter-sectoral interdependencies do not form a closed loop, making cascade effects occurring recursively as described by Kotzanikolaou et al. (2013) impossible.

5.1.3 Cascade distance

Both in the case with and without a temporal component in the model a notable finding is that network failure almost exclusively occurs within inundated areas. Failure in flooded areas is not necessarily direct, as assets do not always get inundated past their critical water depth. These assets however often do fail indirectly as a result of cascade effects from the direct failure in their vicinity. Assets located outside of the study area are generally less affected by indirect failure. This is also reflected by network FA-values generally being slightly higher than the fraction of inundated land in the study area. Almost complete failure occurs within flooded areas and smaller effects happen beyond the impacted regions. Infrastructure failure distant from the inundated area is of extra interest because in realistic situations flooded areas and their surroundings are likely to be evacuated so loss of service in these areas is of lesser importance. When reconfiguration potential is taken into account for the electrical networks, the only substantial failure occurrence outside of the directly affected area happens in the gas network.

One of the reasons for the low prevalence of failure distant from the flood event, is the way networks are structured in the case study area. The dominance of intra-sectoral interdependency limits the potential for failure traversing network boundaries and therefore also for creating distance from the initial failure. Additionally, especially in the medium voltage and gas network, a small number of source nodes supply a relatively large amount of demand nodes. These networks have a sub-networks are mixed structure so most demand nodes are only connected to a single source. Therefore failure of this source triggers failure in all connected nodes which introduces a certain degree of randomness where failure of some nodes results in outages for entire municipalities while others only yield very local effects. Since most essential source nodes for both the medium voltage and gas network are not flood prone, failure distancing itself from the flood event is barely encountered in this study.

5.1.4 Mitigation

When a temporal dimension is included in the model, an important factor that is taken into account is reconfiguration of the medium voltage network. By activating redundant connections, indirectly failed assets can have their power restored. This is only done in the medium voltage network but due to other networks being physically dependent of this network, restoration in the low voltage and telecoms networks can be achieved indirectly.

In the model potential reconfigurations are checked against two conditions. Assets where switches need to be activated need to be accessible by road and completely uninundated. However, it was found that in this case study these conditions never restrict power restoration. While sometimes a potential reconfiguration can not be achieved because of these conditions, the flood development in a later time step would undo the effects achieved by this reconfiguration. When assets are unaccessible or inundated below their critical water depth, this indicates flood development in this area is still actively ongoing so these assets are likely to directly fail in the near future, undoing the effects of mitigation.

Reconfiguration is able to accomplish significant reactivations in multiple networks, e.g. 41% reduction of indirect asset failure in the medium voltage network is achieved for certain flood events. However, it is dubitable to what extent mitigation can be performed in a realistic crisis situation such as a dike breach. In the modeling context all asset failure and accessibility information is readily available. This is used to reconfigure the network using a predefined method. In reality the information availability to network operators is uncertain, which potentially makes the mitigation results achieved in this study overly positive.

5.2 Model applicability

The goal of this study is to develop a methodology to simulate cascade failure in multiple infrastructure networks that occurs after a flood event. While being tested for a select number of networks, aim for this methodology is to be generic for location as well as choice of infrastructure networks. This section reflects on model performance and extension of the approach beyond this case study.

5.2.1 Modeling approach

A topology-based simulation model has been used to simulate failure effects in multiple interdependent infrastructure networks. This modeling approach and the premises that are introduced to uniformly describe failure in different networks bring about differences between simulation results and realistic scenarios. As found in the elicitation process, premises which concern the occurrence of indirect failure cause the largest differences while premise which describe direct failure have a smaller influence on this difference.

The absence of flow modeling within networks is found to be a major contributor to model inaccuracy in the expert elicitation process. The most commonly mentioned reason for this is source nodes will likely lack the production capacity to replace each other in case one of them fails. This makes the modeling approach better suitable in networks with a mixed or sub-networks network structure, as in this case there are few interconnected source nodes which could take over each others function in the simulation. In this case study, source node replacement can potentially happen in the gas network as it has a mixed network structure or in the medium voltage network through reconfiguration. However, in all the applied flood events no instances of this happening have been encountered. In cases where source nodes are susceptible to flooding and display a higher level of interconnection, accuracy of model results decreases.

Another effect mentioned by numerous experts which the current model is unable to account for is the demand increase that can occur in some networks. Especially in telecoms and transportation a natural hazard can cause a drastic increase in network usage, conceivably even in advance of the actual event. This peak demand can cause network congestion severely limiting functionality. With the current modeling approach, this effect can not be simulated due to the inability to describe network flow and because some source of direct failure is required to trigger cascade effects.

5.2.2 Data availability

An advantage of the selected modeling approach is the relatively small necessity for data. Network topology is sufficient to analyze failure in a single network. Analysis of multiple networks requires additional information about connections between assets of different networks, although in this study this was covered by the assumption that assets are connected to the closest asset of another relevant network, e.g. radio masts are connected to the closest low voltage asset. Lastly, some critical water depths must be assigned to assets as a condition for direct failure. However, through sensitivity analysis it is found variations in asset critical water depths do not have a large impact on results so assumptions on critical water depths suffice.

Although the data requirement for this modeling methodology is fairly small, availability of data can pose an issue. Topologies of infrastructure networks are usually only accessible through network operators which can be many different parties in a case study area. Although an increasing amount of information is becoming openly available, a complete overview of infrastructure failure after a flood event requires data and cooperation of numerous different network operators.

For application of this modeling methodology within a case study it is advised to create an overview of critical infrastructure networks and their operators. Following, an analysis should be performed on to what extent network topologies are available and how these networks can be affected by a flood, either directly or indirectly. Before model creation it should be clear what networks are to be included and what interdependencies exist within and between these networks.

5.2.3 Network-specific modeling

This study aimed to encapsulate multiple networks using the same modeling methodology as to describe their failure patterns in a similar manner. However, it was found unattainable to model failure in all networks in a completely identical way. Differences between infrastructure networks were reason to introduce network properties. However, the different options for these properties are based on the infrastructure networks encountered in this study. If other networks are to be incorporated into this modeling approach it is possible they would not fit within the currently defined network properties. While this study aimed to generally describe and model infrastructure networks, some essential differences between infrastructures are encountered. For this reason individual approaches are always required to accurate similar failure in infrastructure networks.

Multiple experts state substantial model improvements would require addition of more network- and location-specific information, which would stray away from the goal of producing a uniformly applicable methodology. Some of these additions could fit within the current modeling approach while others would require redefinition of model premises. Specifically the premise that no network flow is simulated hinders introduction of more network-specific failure behavior. A generic approach to network flow modeling has been applied by Lee et al. (2007) but does require additional and more detailed location-specific knowledge, e.g. production capacity of source nodes and transportation capacities of links.

5.2.4 Model aptitude

Implementation of failure behavior which is more specific to the selected location and networks is possible, although it would in some cases require reformulation of model premises. Addition of certain aspects such as source node replacement or influence of evacuation on network demand could provide more accurate representations of complications that occur in critical infrastructure during natural hazards. However, this does introduce a need for detailed understanding of specific network failure patterns which unavoidably introduces a need for additional assumptions, introducing new forms of uncertainty.

Whether such additions to the modeling methodology are required depends on the questions that a study on cascade failure aims to answer. Experts state the current model is able to answer basic questions concerning network operation, such as asset functionality and accessibility. More complex questions however, would require inclusion of phenomena the model is currently unable to take into account. For instance, the methodology applied in this study can not be used to study whether networks can handle an evacuation procedure or if certain areas can still retain their socioeconomic function in case of a nearby flood.

Finally, the applied methodology is also limited in the temporal dimension. Only the first 48 hours of a flood event were simulated in this study during which all mitigation aimed at crisis management instead of complete restoration. Both failure effects in advance of the dike breach and return to normal operation after the flood event has passed fall outside of the modeling scope.

5.2.5 Future application

During application of the modeling methodology in the current case study it is found most failure occurs within and close to inundated areas and intra-sectoral interdependencies are most influential in asset failure. These effects are partly attributed to network selection and attributes of the study area which has a mostly rural nature with low infrastructure asset density. An important future extension to this study would therefore be application of the same modeling approach in a setting where networks are more strongly interconnected and where key source nodes are more flood prone. This could provide an indication what effects result from the disposition of the case study area and what results occur more naturally in infrastructure networks or result from the modeling methodology. A slightly smaller study area with higher infrastructure density is advised.

Experts state that in many cases the modeling methodology is relatively easily translated to beyond the current study area, also for more urban settings. Network structure and operation are said not to be fundamentally different for urban areas. Higher asset density can however lead to more source node interconnection which as previously described decreases result accuracy due to the absence of network flow modeling.

In model applications in other study areas, the geographical scope can be more ambiguous. Zeeuws-Vlaanderen has clear natural and geographical borders, making the selection of what assets to include straightforward. Still, even in this setting events outside the study area can lead to network failure. For other study areas geographical borders are likely less defined and can strongly differ per network. Coherent and distinct border definition is critical in order to comparatively assess network failure. Lastly, observations concerning data requirement and modeling goals should be taken into account in future model applications.

6 | Conclusions

Interdependency between critical infrastructure networks increases their vulnerability to cascade failure. A topology-based simulation model was found to be the optimal choice to generically simulate cascade effects in critical infrastructure networks. To uniformly simulate failure behavior network properties are defined which describe fundamental differences between infrastructure. These properties however are unable to describe all diversity in infrastructure networks, so network-specific approaches are required to adequately simulate failure. Furthermore, model premises are established to facilitate the generic modeling approach. These premises aim to uniformly describe how cascade effects occur in all networks.

In the case study it is found that both direct and indirect failure are largely confined to inundated areas, with direct failure generally accounting for the largest share. These effects are attributed to the fact that few failures occur high in the network hierarchy, limiting magnitude of cascade effects. This effect is realistic to an extent as key source nodes in the case study area are typically not vulnerable to floods because of their geographical location. However, simulation of widespread failure is also limited by the exclusion of higher order networks in the analysis. Accordingly, most indirect failure occurs as a result of intra-sectoral cascade effects while interdependency between different infrastructure networks has less influence. Reduction of indirect failure can be achieved by adding more network redundancy as the potential for cascade effects decreases when more node connection routes are available.

The modeling methodology applied to generically simulate cascade effects results in disparity between failure occurrence in simulation and during realistic flood events. Herein, model premises regarding how assets are directly affected by flood events are considered to be of lesser influence than premises that describe in what way cascade effects emerge. Especially the absence of network flow modeling is a cause of inaccuracy as source nodes generally lack the production capacity to replace each other when one of them fails. Furthermore this premise causes the model to neglect the demand increase that occurs with disaster situations in certain networks.

The applied modeling methodology is appropriate for predicting infrastructure asset performance during a flood event. Especially for networks with a clear single function such as the electrical or gas network, this gives a locationally explicit indication of network functionality. For networks with a broader function such as the telecoms and transportation network asset failure provides a less clear indication of to what extent a network is still able to perform.

A suggested future study is model application in a setting with higher infrastructure density where key source nodes are more vulnerable to flood events, in order to simulate more widespread failure. Herein and in all future studies on critical infrastructure failure it is advised to identify goals of the analysis and key failure processes in advance of model application. Based on modeling goals and setting where the model is applied the network selection, geographical scope and level of generality should be chosen.

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Appendices

A. Flood events

Flood events used in this study are extracted from the Lizard Flooding portal of Nelen & Schuurmans. This portal contains detailed flood information for floods simulated as a breach occurring in each representative dike section in Zeeuws-Vlaanderen. These simulations are in most cases available for different outside water levels, ranging from recurrence probabilities of once in 400 years to once in 400000 years.

A.1 Flood events non-temporal model

When temporal aspects are not taken in account, the model uses flood maps which contain maximum inundation depths. Five breach locations are selected which are approximately evenly spread over the case study area. All chosen locations have flood simulations for four different outside water levels, with increasing recurrence times. Selected breach locations are Breskens, Paulinapolder, Dow Terneuzen, Margarethapolder and Kruispolder. Inundation maps of breaches at these locations are combined based on outside water level recurrence probability and used as model input. The following figures show inundation maps for each recurrence probability. These maps display maximum inundation depth reached over a flood duration of 144 hours at a spatial resolution of 25 by 25 meters.

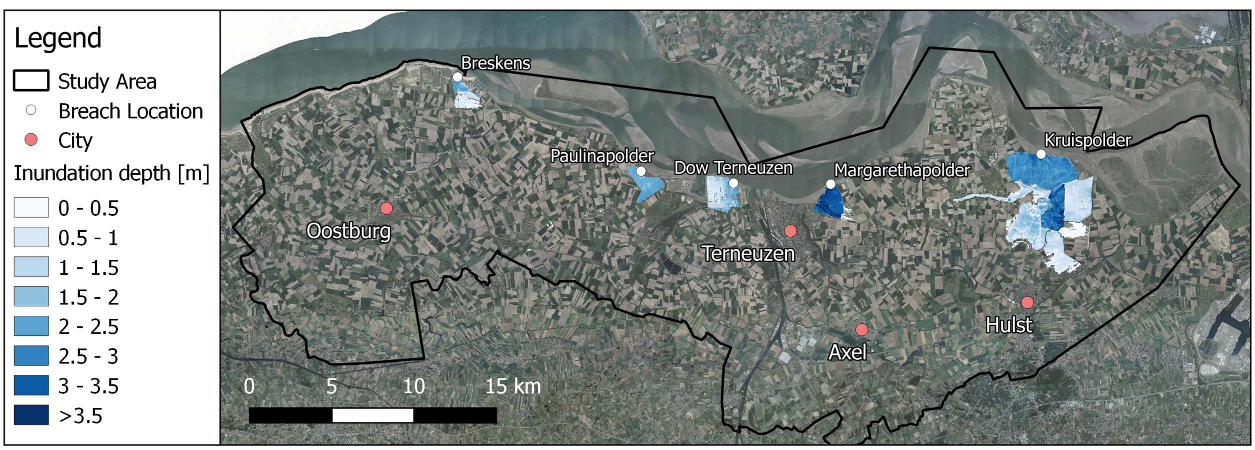


Fig. A.1: Inundation map of flood event with five simultaneous breaches and an outside water level with a return period of 400 years.

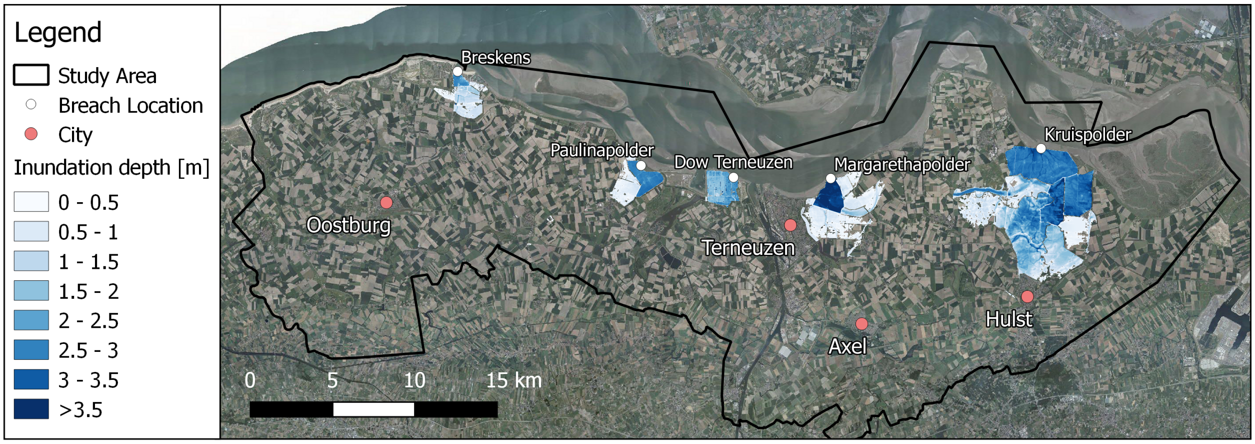


Fig. A.2: Inundation map of flood event with five simultaneous breaches and an outside water level with a return period of 4000 years.

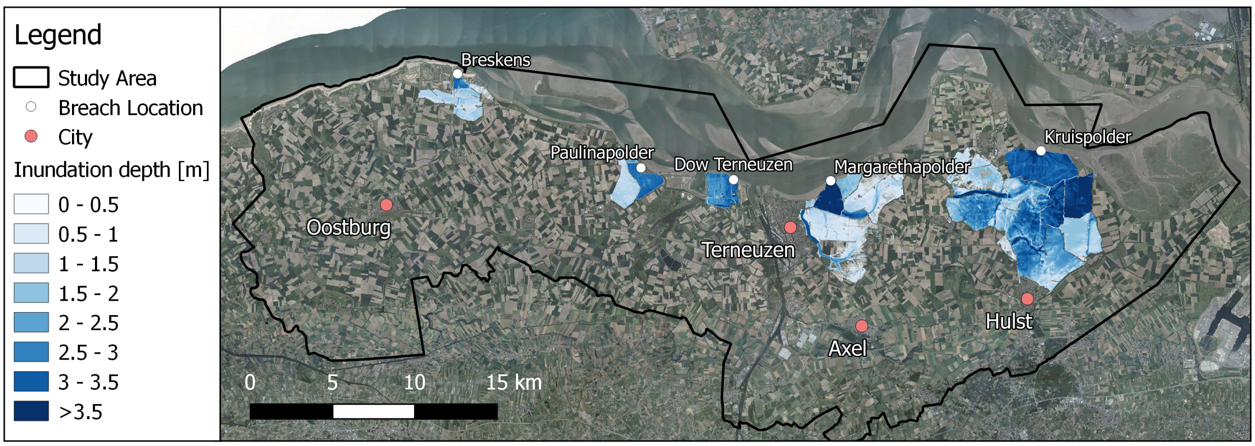


Fig. A.3: Inundation map of flood event with five simultaneous breaches and an outside water level with a return period of 40000 years.

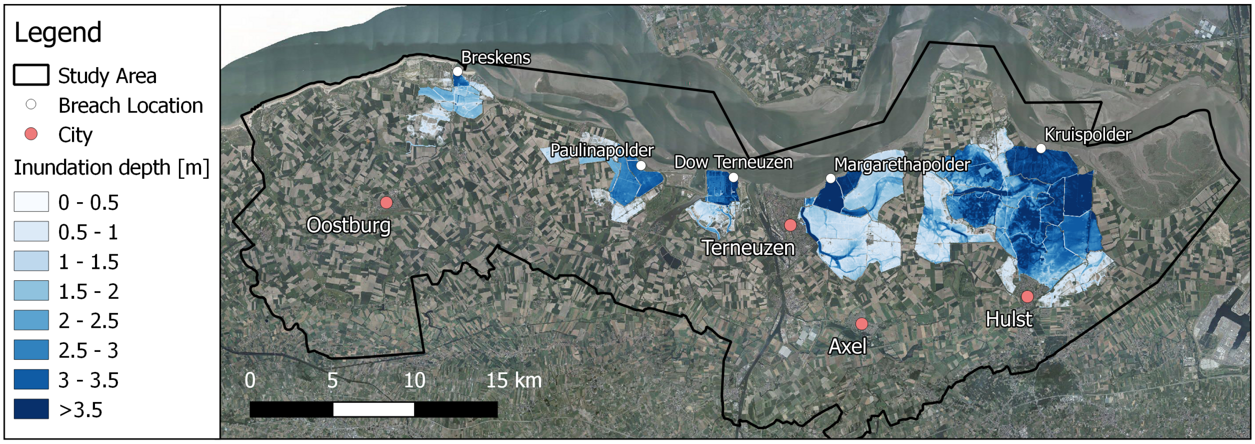


Fig. A.4: Inundation map of flood event with five simultaneous breaches and an outside water level with a return period of 400000 years.

The selected flood events represent escalating levels of disaster in the case study area. Table A.1 shows inundation statistics for these flood events.

Table A.1: Inundation statistics of selected flood events within the case study area. Inundated areas are given as absolute values and as a percentage relative to the total size of the study area.

Recurrence time	Inundated area	Percentage
400 years	30.1 km^2	3.4%
4000 years	45.7 km^2	5.2%
40000 years	79.9 km^2	9.1%
400000 years	124.6 km^2	14.2%

A.2 Flood events temporal model

When temporal aspects of a flood are taken into account, instead of maximum inundation depth hourly inundations are used. In this case, two of the previously described breach locations are selected to analyze the failure they lead to. These breaches are at Breskens (westernmost) and Kruispolder (easternmost). Reason for selection of these flood events is that they inundate a rather small (Breskens) and a rather large area (Kruispolder) and furthermore have dissimilar flood development. Fig. A.5 shows the cumulative volume that has flowed into the study area, the total inundated area and the average inundation depth per time step of one hour. While data is available for 144 hours for both flood events, it is found that after 48 hours further flood development yields little changes.

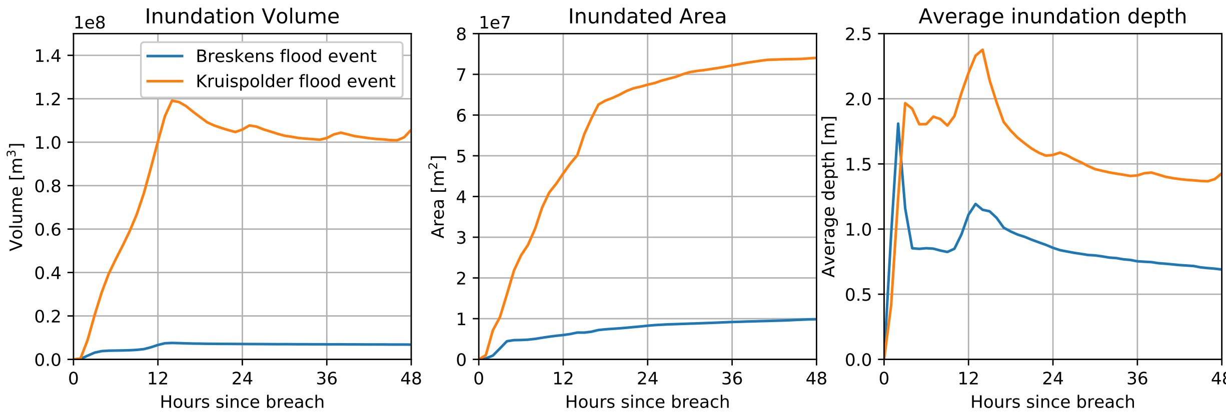


Fig. A.5: Temporal progression of relevant flood parameters of floods used in model with temporal component. Flood events are the western- (Breskens) and easternmost (Kruispolder) floods in previous figures.

A.3 Flood event overview

Numerous flood events are used to analyze failure in infrastructure networks in the case study area. Table A.2 provides an overview of all events used for different applications of the model.

Table A.2: Overview of flood events used for various model runs in this study, in order they are encountered in Chapter 3

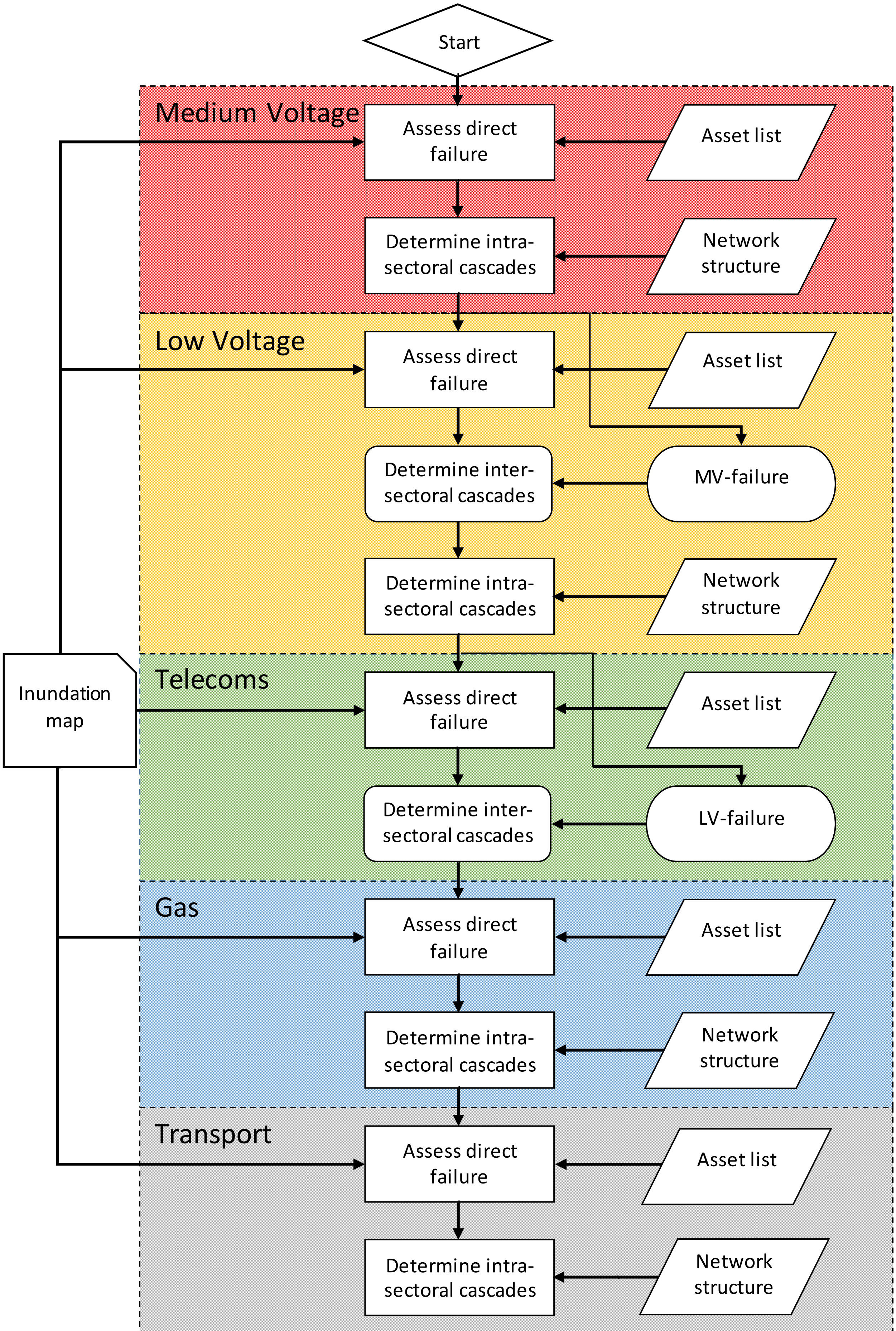
Application	**Dike breach**	**Return time**	**Duration**	**Mitigation**
Reference case	5 simultaneous	400000 years	Static	No
Temporal failure development	Breskens	400000 years	48 hours	Normal
Temporal failure development	Kruispolder	400000 years	48 hours	Normal
Sensitivity flood size	5 simultaneous	400-400000 years	Static	No
Sensitivity asset critical depth	5 simultaneous	400000 years	Static	No
Sensitivity mitigation	Breskens	400000 years	48 hours	3 options
Sensitivity mitigation	Kruispolder	400000 years	48 hours	3 options

B. Model flowchart

The chart on the next page shows the modeling steps taken for a single run of the model without a temporal component. Note that the process for each network starts with the assessment of direct failure. Here the inundation map is compared with the asset list which contains the critical water depth for each asset. When the direct failure has been determined the process per network differs. Be aware of the differences in the flowchart between determining intra- and inter-sectoral cascades. The low voltage and telecoms network have a dependency on another network, so for these networks first the cascade effects following from failure in the preceding network is determined. When there is no dependency on another network, intra-sectoral cascade effects are be determined. The low voltage network has both intra- and inter-sectoral interdependencies, so here both steps are applied.

When a temporal component is included in the model, this process is repeated for every time step with a new inundation map. Furthermore some extra steps which are not indicated in this flowchart are required.

- Directly failed assets are stored in memory, and set as directly failed in advance of each time step. This ensures that directly failed assets are kept as such, even if in later time steps they do not get inundated past their critical water depth. This is not done for the transportation network, as roads can become accessible again after having been inundated.
- Reconfiguration in the medium voltage network is done after each time step. Using previously determined failure in the medium voltage and transportation networks, the network structure of the medium voltage network is updated. This new network structure is then used when the process is repeated for the next time step.
- All asset failure is saved after each time step to be able to regard failure development over time.


Start
Medium Voltage
Assess direct failure
Asset list
Determine intra-sectoral cascades
Network structure
Low Voltage
Assess direct failure
Asset list
Determine inter-sectoral cascades
MV-failure
Determine intra-sectoral cascades
Network structure
Inundation map
Telecoms
Assess direct failure
Asset list
Determine inter-sectoral cascades
LV-failure
Gas
Assess direct failure
Asset list
Determine intra-sectoral cascades
Network structure
Transport
Assess direct failure
Asset list
Determine intra-sectoral cascades
Network structure

C. Additional figures temporal flood progression

Fig. C.1 and C.2 show temporal progression of asset failure in the medium voltage and gas networks from the Kruispolder flood event. In the medium voltage notice assets which have indirectly failed at 10 hours but which have reactivated through network reconfiguration at 15 hours. In the gas network notice the total amount of failed assets is equal at 10 and 15 hours after the dike breach. However, the assets continue to fail directly after having previously failed indirectly.

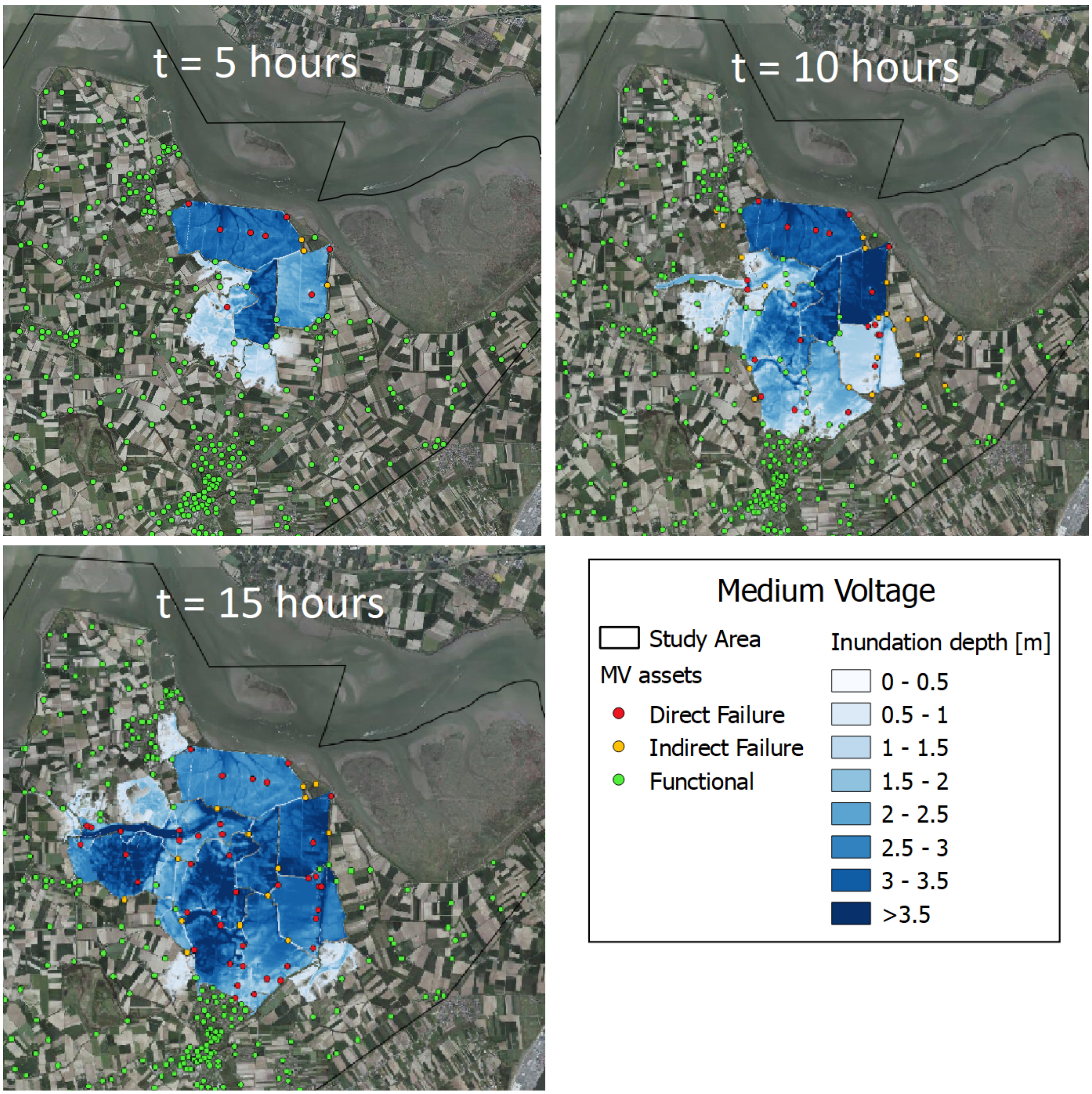


Fig. C.1: Temporal progression of failure in the medium voltage network in the Kruispolder flood event, times are hours since the dike breach.

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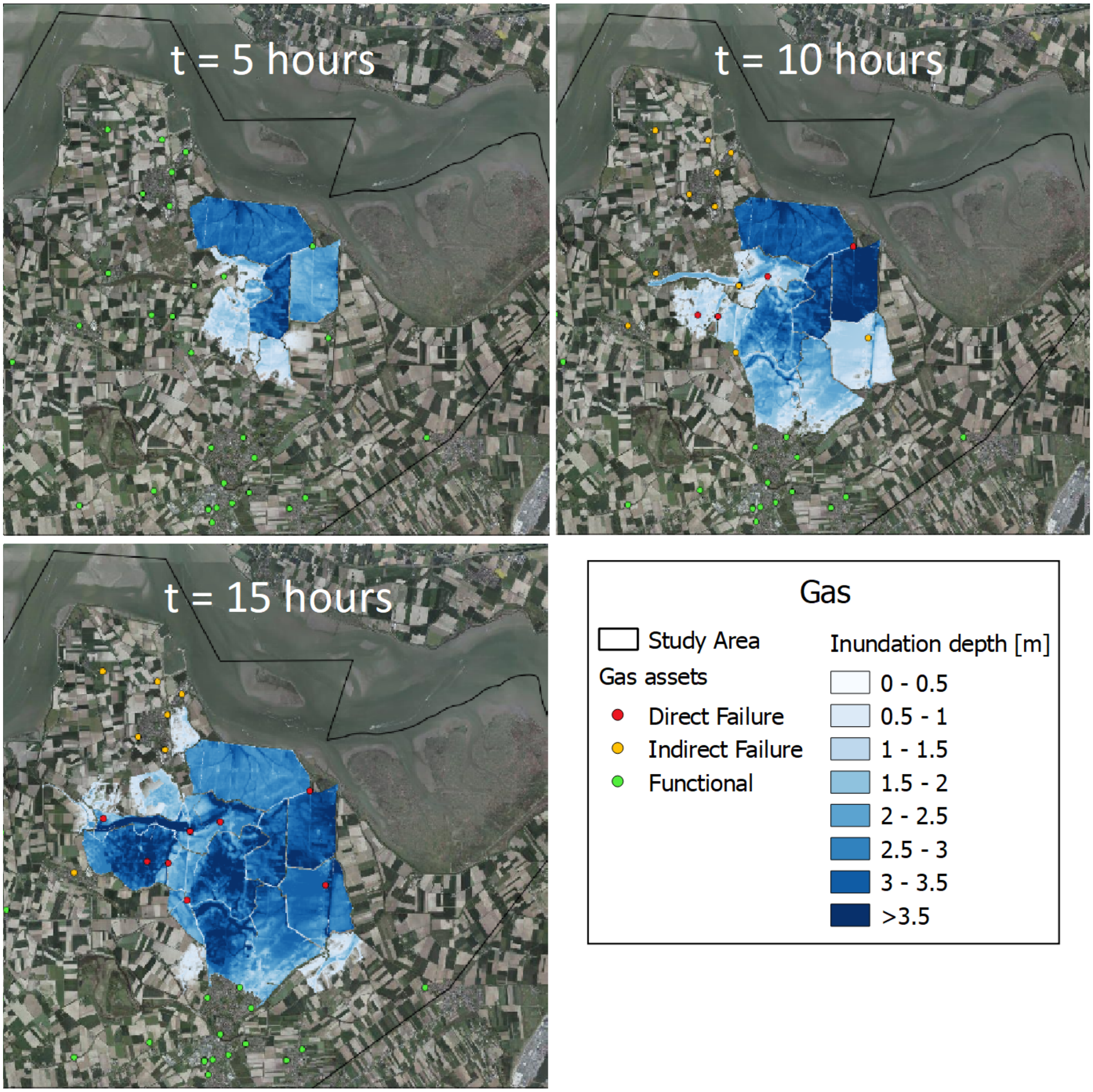

Fig. C.2: Temporal progression of failure in the gas network in the Kruispolder flood event, times are hours since the dike breach.

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D. Additional figures network reconfiguration

Network reconfiguration is the driving force for restoration of power in the medium voltage network. Due to the dependency on medium voltage electricity, restoration of medium voltage assets also restores power in the low voltage network. Restoration of low voltage assets can in turn drive reactivation of radio masts in the telecoms network. Similarly to failure, effects of mitigation in the medium voltage network can cascade to other networks. Additional figures to highlight sensitivity for network operations in other networks and for another flood events are provided in this appendix.

D.1 Kruispolder flood event

Sensitivity of electrical network failure parameters for reconfiguration options in the medium voltage network using the Kruispolder flood event as cause of failure.

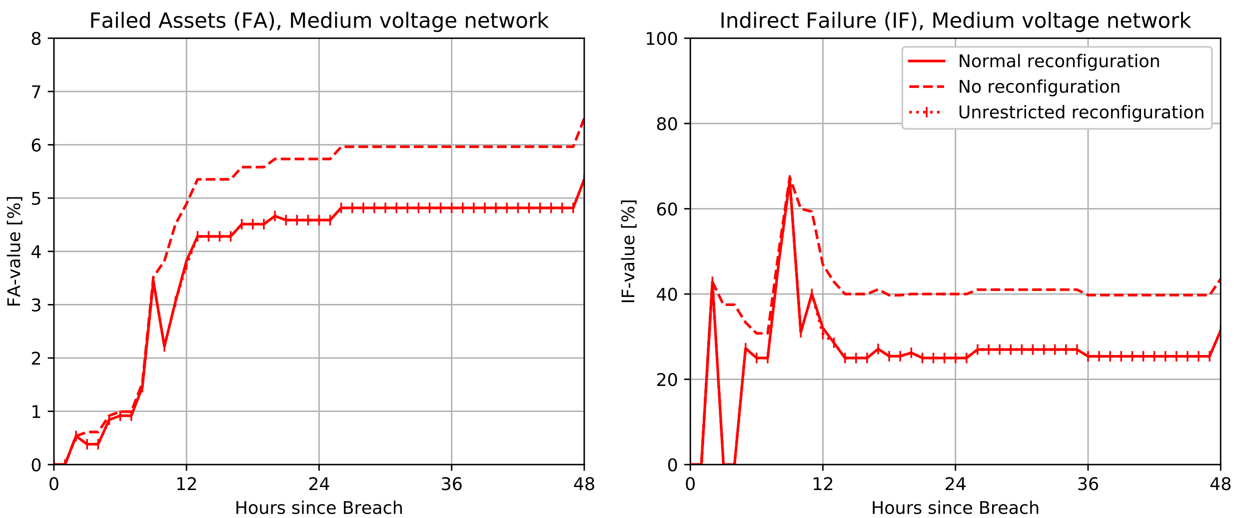

Fig. D.1: Influence of different reconfiguration options on the progression of medium voltage failure parameters following from the Kruispolder flood event

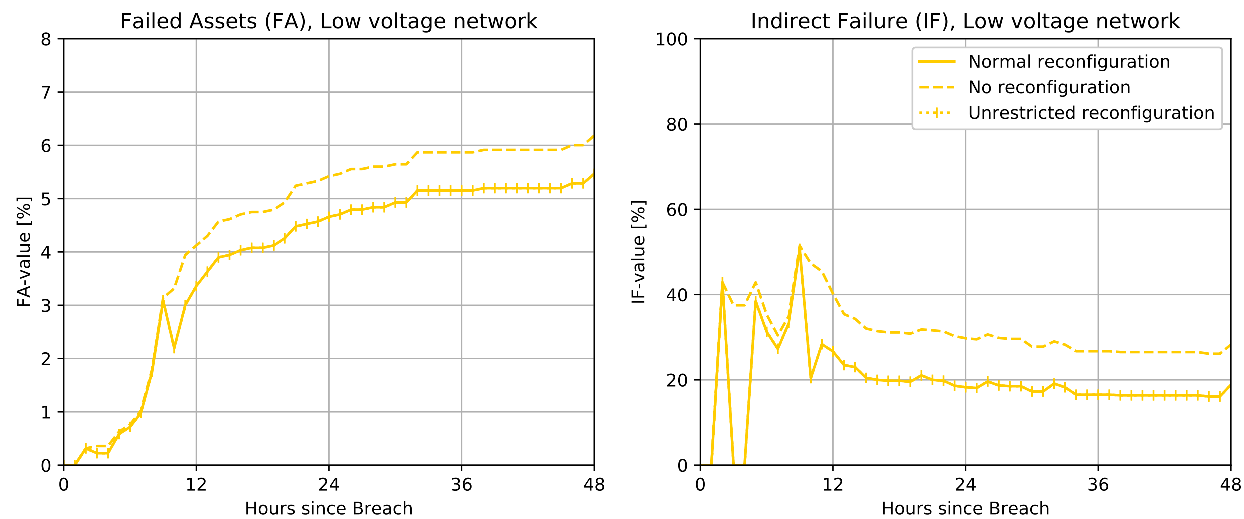

Fig. D.2: Influence of different reconfiguration options on the progression of low voltage failure parameters following from the Kruispolder flood event

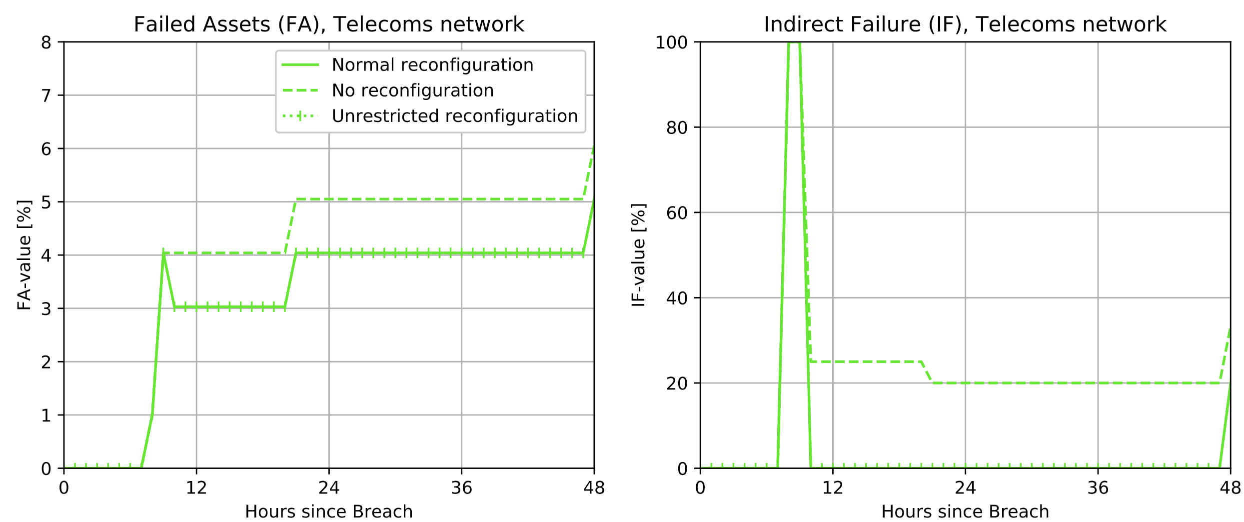

Fig. D.3: Influence of different reconfiguration options on the progression of telecoms parameters following from the Kruispolder flood event

D.2 Breskens flood event

Here the same figures are provided but now using the Breskens flood event as the cause of failure.

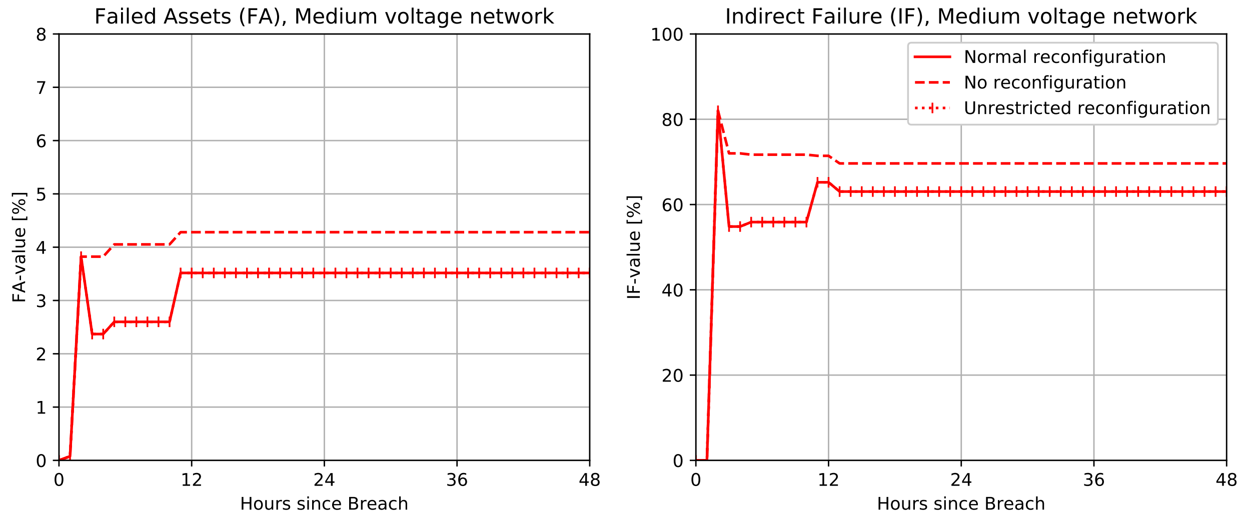

Fig. D.4: Influence of different reconfiguration options on the progression of medium voltage failure parameters following from the Breskens flood event

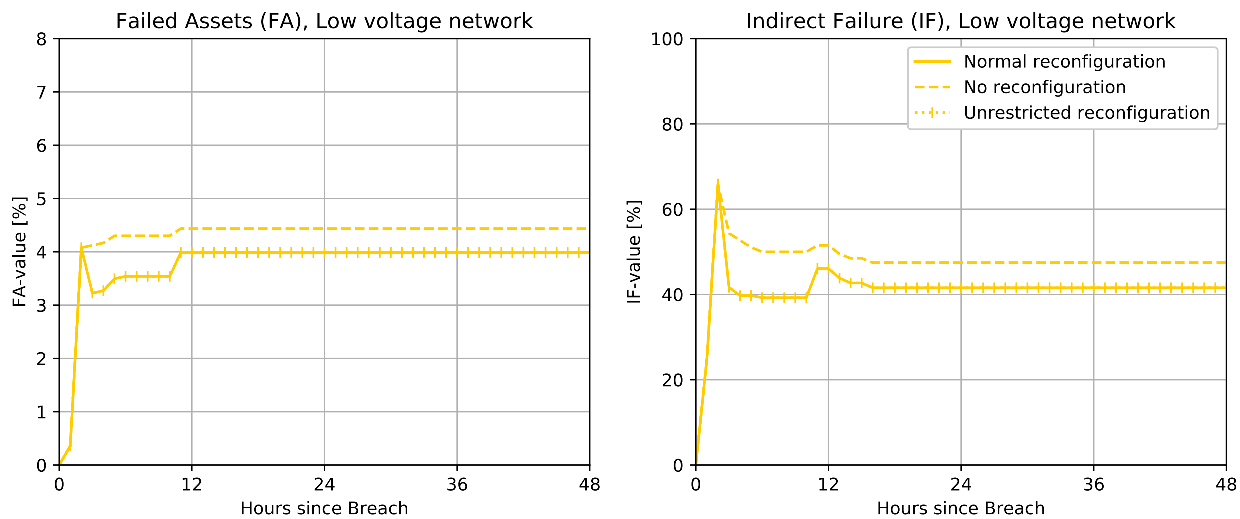

Fig. D.5: Influence of different reconfiguration options on the progression of medium voltage failure parameters following from the Breskens flood event

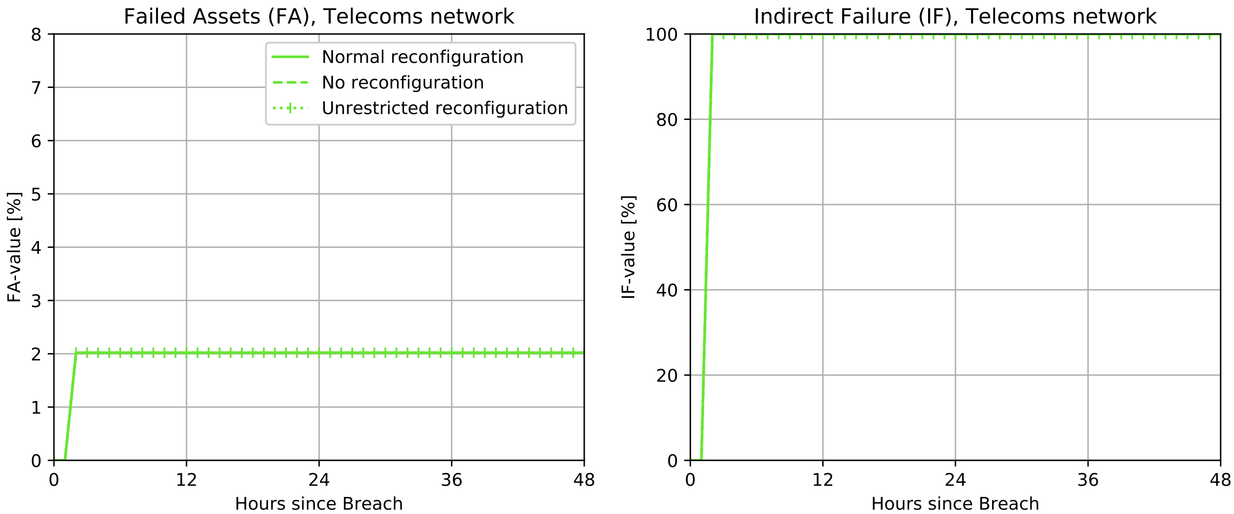

Fig. D.6: Influence of different reconfiguration options on the progression of telecoms failure parameters following from the Breskens flood event