UNIVERSITY OF TWENTE.

Faculty of Engineering Technology

Risk analysis of interdependent Critical Infrastructures to Extreme Weather Events

MASTER OF SCIENCE THESIS

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s1662430

March 2017

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Abstract

Growing scientific evidence suggests that risks caused by critical infrastructure (CI) failure will increase worldwide due to more frequent and intensive extreme weather events (EWEs) induced by climate change. Those risks are difficult to estimate due to the increasing complexity and interconnectedness of CIs and because information sharing regarding the vulnerabilities of the different CIs is limited. This paper proposes a methodology for risk analysis of systems of interdependent CIs to EWEs and climate change, as developed and carried out for the Port of Rotterdam area in the Netherlands. The case study includes multiple CIs that belong to different sectors and can be affected at the same time by an initiating EWE. Therefore, the methodology proposed supports the assessment of common cause failures that cascade across CIs and sectors, based on a simple, user-friendly approach that can be used by CI owners and operators. From the case study it became clear that the severity of cascading effects is strongly influenced by the states of operation of the different CIs during and after the initiating EWE and that there is a need to raise stakeholders' awareness of systemic risks.

1 Introduction

Extreme weather events (EWEs) constitute a potential threat for vulnerable human and natural systems and they are expected to increase in terms both of frequency and intensity due to the warming of the climate system (IPCC, 2012). EWEs and climate change are among the most prominent global risks, lying in the higher-impact, higher-likelihood quadrant (World Economic Forum, 2017) and they can induce hazards such as flooding, drought, ice formation and wild fires, which present a range of complex challenges to the operational resilience of Critical Infrastructures (CIs), (Vangelsten et. al, 2014).

An extreme climatic event is usually defined as one that is rare within its statistical reference distribution at a particular place and time, normally be as rare as or rarer than the 10th or 90th percentile of the observed Probability Density Function (IPCC, 2007). For events related to infrastructures, the characterization of weather event as extreme is performed according to thresholds critical for infrastructures (Bucchignani & Gutierrez, 2015). As CIs are regarded "those infrastructures whose services are so vital that their disruption would result in a serious, long-lasting impact on the economy and the society", (EC COM (2004) 702 final). Physical CIs include large scale, spatially distributed, complex networks, like energy supply, transportation, information and telecommunication, water and solid waste systems (Eidsvig & Tagg, 2015; World Economic Forum, 2017). Those systems are vulnerable to extreme climate variables, since most of them have been designed under the assumption that climate is stationary (Klein Tank & Zwiers, 2009). Moreover, they are highly interconnected and heavily dependent upon each other and therefore a disruption in any of these systems can cascade across infrastructures and affect the functioning of the entire system of CIs, (Rinaldi, Peerenboom & Kelly, 2001; Bouchon, 2006; IPCC, 2012; Eidsvig & Tagg, 2015; World Economic Forum, 2017)

As climate becomes extreme it is likely that risks for CI failure will increase worldwide (Bouwer, 2013; Eidsvig & Tagg, 2015). Analysing and assessing the risks posed to CIs by EWEs on the basis of future climate scenarios can help in establishing a good basis for decisions regarding risk reduction, monitor and control (Aven, 2003). However, the increasing complexity and interdependency of CI systems makes the severity of those risks very difficult to estimate; moreover, CIs owners and operators tend to understand their own systems very well but usually are not aware of the resilience of the CIs that they are connected to (World Economic Forum, 2017). Existing risk assessment methodologies that account for dependencies among CIS and address risks across different sectors are rather limited, (Giannopoulos, Filippini & Schimmer, 2012), while future climate scenarios are barely considered (Gallina et al., 2016).Furthermore, if such methodologies are to be used from stakeholders, they should be user friendly, even when analysing complex, large systems, (Utne, Hokstad, & Vatn, 2011).

This paper describes a methodology for risk analysis of interdependent critical infrastructures to EWEs and climate change, as developed and carried out for the Port of Rotterdam area in the Netherlands. The methodology aims at CIs owners and operators and makes use of stakeholders' experiences regarding former decision-making situations, earlier EWEs and their impacts on infrastructures, as well as of existing risk assessments on the CI or sector level. The work constitutes part of the EU-FP7 project with the acronym INTACT; the project addresses the resilience of Critical Infrastructures to Extreme Weather Events challenges and intends to bring together innovative and cutting edge knowledge and experience in Europe to support stakeholders throughout Europe (and beyond) on risk assessment regarding EWEs and climate change and on decision making regarding risk mitigation options for their CIs, (Vangelsten et. al, 2014). In order to do so, case studies were selected across Europe that encompassed different climate, landscape and environmental zones to provide coverage of a representative range of CI types and different levels of governance (van Ruiten, Bles, Kiel, 2016). For this purpose the Port of Rotterdam area in the Netherlands was selected as one of the appropriate case studies, as it includes multiple CIs that belong to different sectors and are exposed to different types of extreme weather.

The rest of the paper unfolds in the following way. Section 2 presents the definitions of the different terms as used in the study and reviews and summarises existing approaches for Risk assessment methodologies for CIs. Section 4 describes the risk analysis methodology proposed in this study, while Section 5 presents the detailed implementation of the methodology in the case study. Finally, in Section 6 the methodology and potential future research work are discussed.

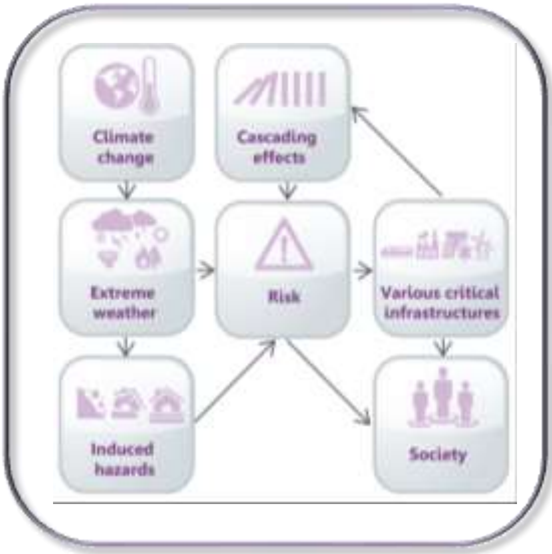


Figure 1 Relevance of Climate change for CIs ("INTACT_Wiki", 2017)

2 Literature review

2.1 Risk analysis

According to ISO Guide 73, (2009), risk is generally defined as "the effect of uncertainty on objectives" and is often characterized by reference to potential events and consequences. In the context of this study risk refers to the "the result of a threat with adverse effects to a vulnerable system", (Haimes, 2006). Threat or hazard is defined as a source of harm or danger (Kaplan & Garrick, 1981; ISO Guide 73, 2009), while vulnerability is interpreted by most authors as the predisposition of a society or a system to be negatively affected by single or compound hazard events. Birkmann et al., (2013) argued that in the context of natural hazards and climate change vulnerability should be described by key factors such as "the exposure of a society or system to a hazard or stressor, the susceptibility of the system or community exposed, and its lack of resilience". Exposure refers to the extent to which a unit of assessment falls within the geographical range of a hazard event and is qualified in spatial and temporal terms; susceptibility (or fragility) describes the predisposition of elements at risk to suffer harm and it has multiple dimensions, such as physical, ecological, social, economic, cultural and institutional; finally, resilience refers to the capacity of a society or a system to anticipate, cope and recover in response to a hazard event, (Birkmann et al., 2013).

Risk analysis forms part of the overall process of risk assessment and can be defined as a process to comprehend the nature of risk and to determine its level or magnitude (ISO Guide 73, 2009). According to Kaplan & Garrick, (1981), the goal of a risk analysis is to answer three questions:

1. "What can go wrong?"
2. "How likely is it that that will happen?"
3. "If it does happen, what are the consequences?"

In order to answer these questions one should identify relevant scenarios and estimate the probability of occurrence and the consequences of those scenarios. Scenario can be defined as "a hypothetical situation consisting of an identified threat or hazard, an entity impacted by that hazard, and associated conditions including consequences, when appropriate" (FR).Probability can be interpreted either as a relative frequency or as a subjective measure of uncertainty about future events and outcomes (Aven, 2007).The probability of hazards induced by EW is often expressed as a return period or recurrence interval that gives the estimated time interval between events of a similar size or intensity ("Return Periods of Extreme Events - Climatica", 2017) and there are several well established methods to assess the magnitude and probability or return period of weather related single-hazards (WMO, 1999; Gallina et al., 2016). However, the data usually used for hazard assessment are historical information of previous events, while future climate scenarios are not considered (Gallina et al., 2016). Moreover, there are several sources of uncertainty regarding future climate information that arise from natural climate variability, uncertainty regarding future emissions of greenhouse gases and modelling uncertainty, ("Uncertainty guidance topic 1 — Climate-ADAPT", 2017).

When it comes to CIs, impact refers to "the severity of the consequences of an unwanted event, and in particular the level of disruption and/or destruction of infrastructure", (EC COM (2006) 787 final) and may be substantially different to the system owner, to the system users and to the society, (Utne, Hokstad, & Vatn, 2011; Theoharidou & Giannopoulos, 2015). The European Commission defined the following impact criteria for CI assessments: (i) public effect (ii) economic effect (iii) environmental effect (iv) political effects and (v) psychological effects on the population, (EC COM(2006) 787 final). These criteria are evaluated in terms of scope (local, regional, national and international) and time (during and after the incident), (Theoharidou, Kotzinikolaou & Gritzalis; cited in Palmer & Shenoi, 2009). Most authors classify economic effects or costs of natural hazards in tangible and intangible and further in direct and indirect (McKenzie et al., 2005; Middelmann, 2007; Hallegatte & Przyluski, 2010). Intangible costs refer to damages to goods and services which are not easily measurable in monetary terms (Meyer et al., 2013). Direct costs are caused by a disaster during the actual event and include for example, the direct damages due to complete or partial destruction of physical assets, as well as fatalities and injuries. Indirect impacts are flows of impacts that occur over time after a disaster or outside the place of disaster (Meyer et al., 2013) and they can be particularly serious in case that a CI is affected by the disaster, (Fekete, 2011; Heilemann et al., 2013).

The level of risk can be estimated by using qualitative, semi-quantitative or quantitative assessment methods; semi-quantitative methods combine impact and probability to produce the level of risk, using numerical rating scales while quantitative analysis estimates practical values for impact and probability and produces values of the level of risk in specific units (ISO/ IEC 31010:2009, 2009). Quantitative risk analysis produces a ''best estimate'' or "best assignment" of risk, since the actual risk values are not known and that the value added by the quantification is not warranted (Aven, 2008).

2.2 Existing risk assessment methodologies for CIs

Risk assessment methodologies for CIs can be broadly categorized in Sectoral methodologies that address the risks on the sector or even asset level and Systems approach that assess the CIs as an interconnected network (Giannopoulos, Filippini & Schimmer, 2012). The existing risk assessment methodologies for CIs that account for dependencies among infrastructures are rather limited (Giannopoulos, Filippini & Schimmer, 2012). One example that falls into the systems approach is that of Haimes, (2008) which applies risk assessment methodologies to System of Systems (SoS). A SoS approach was also developed by Theoharidou and Giannopoulos, (2015) to address risks from natural hazards on the asset, system and society level. Utne, Hokstad, & Vatn, (2011) on the other hand introduced the DECRIS approach which is a risk and vulnerability analysis method for CIs for multiple hazards across sectors.

2.3 Analysis of CIs dependencies and assessment of cascading effects

An infrastructure dependency can be defined as "unidirectional relationship between infrastructures, where the state of one infrastructure influences or correlates with the state of the other", (Rinaldi, Peerenboom & Kelly, 2001). Moreover, the authors identified and described six dimensions of infrastructure dependencies: i) Types of dependencies, ii) Infrastructure environment, iii) Coupling and response behaviour, iv) Infrastructure characteristics, v) Types of failures and vi) State of Operation. Dependencies can be classified as physical, cyber, logical and geographical. Infrastructure environment refers to the environment that an infrastructure operates, including economic, technical, legal, social, safety, business, security and public policy aspects. Infrastructure characteristics include spatial scales, temporal scales, operational factors, and organizational characteristics. Dependency related failures in CIs can be characterized as cascading, escalating or common-cause failures. A cascading failure occurs when a disruption in one infrastructure causes the failure of one or more components in a second infrastructure, which subsequently causes a disruption in the second infrastructure. A common cause failure occurs when two or more infrastructure systems are disrupted at the same time, for example due to geographical proximity or when the cause of disruption is widespread (Rinaldi, Peerenboom & Kelly, 2001). Nieuwenhuijs, Luiijf & Klaver, (2008) however, argued that dependencies always deal with the relationships between two infrastructures and that common cause scenarios are part of risk analysis and should not be mistaken as a type or an aspect of dependency. Finally, the state of operation of an infrastructure can be thought of as a continuum that exhibits different behaviours and can be characterized as normal, stressed or disrupted and repair or recovery, depending on the operating conditions. In order to understand and analyse infrastructure dependencies it is necessary to determine for each one infrastructure on which others it depends for all the states of operations, (Rinaldi, Peerenboom & Kelly, 2001). Nieuwenhuijs, Luiijf & Klaver (2008) empirically found that CIs have other set of dependencies depending on their operational state.

The analysis and modelling of critical infrastructure dependencies received high attention in the literature especially in the last few years and several approaches have been developed. Ouyang, (2014) broadly categorized modelling and simulation approaches for CIs dependencies into six types: Empirical, Agent based, System dynamics, Economic theory based, Network based and others (hierarchical holographic modelling based, high level architecture based, Petri net based, dynamic control system theory based, Bayesian network based, etc.). In network or graph based approaches CIs are represented as nodes and dependencies as arrows that connect the nodes. Theoharidou, Kotzinikolalou, & Gritzalis (2011) and Kotzinikolalou, Theoharidou & Gritzalis (2013) developed a graph based dependency analysis methodology, in which dependencies are quantified using the impact $I_{i,j}$ and the likelihood $L_{i,j}$, on a Likert scale, of a disruption being realized to infrastructure CI_j due to its dependency on CI_i. The methodology assumes a single initiating event affecting a single CI. Therefore, the value associated to each arrow refers to the first-order dependency risk $R_{i,j}$ for each infrastructure. The risk level of the dependency $R_{i,j}$ is defined as $L_{i,j} \times I_{i,j}$ and is quantified using a risk scale. The main input for the methodology is provided by CIs owners and operators. It is assumed that the operators can assess the impact for their own infrastructures due to a failure in another infrastructure, as they are aware of mitigation measures, back-up systems and the real impact that a disruption will have on their system (Kotzinikolalou, Theoharidou & Gritzalis, 2013).

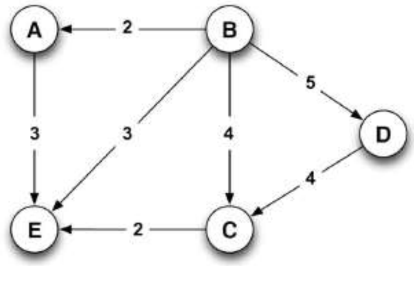


Figure 2 Example Dependency Risk graph between CIs (Kotzinikolalou, Theoharidou & Gritzalis, 2013)

3 Proposed Methodology

This study follows a scenario-based, system approach to analyse risks for interdependent CIs due to EWEs, for the current climate conditions and future climate scenarios. Common cause failures scenarios are regarded as part of risk analysis and not as a dependency type, as suggested by Nieuwenhuijs, Luiijf & Klaver (2008). The level of risk is estimated based on a semi-quantitative method, using a numerical rating scale for impact and percentages for probability or likelihood. The risk analysis methodology described in this study is based on the INTACT Risk Management Process ("INTACT Risk management process - INTACT_Wiki", 2017) that follows the standards for risk process developed by the International Electrotechnical Commission, (ISO/ IEC 31010:2009, 2009) and consists of the following steps:

1. System description

CIs include the organizations of owners, operators and users, the so called human activity systems that are supported by designed physical systems (Checkland, 1999) like energy supply, transportation, information and telecommunication networks, which are highly interconnected. The aim of this step is to understand the nature of the system of CIs, its function and the environment in which it operates and to determine the system boundaries and the level of the analysis required, as the consequences of an unwanted event may be substantially different to the CIs owners than to the society; (Utne, Hokstad, & Vatn, 2011; Theoharidou & Giannopoulos, 2015).

2. Risk Scenarios Identification

The objective of this step is to identify possible risks and to decide on the main scenarios for detailed risk analysis. Since the identification phase can produce several risk scenarios, it is necessary to limit them in a subset (Utne, Hokstad, & Vatn, 2011; Haimes, 2012). This can be done by performing a preliminary risk analysis to identify potential candidates with high risk. In the case of risks due to EWEs the scenarios are usually of low probability and high consequences. The decision on which risk scenarios to consider for further analysis can be based on surveys, analytical hierarchy process , subjecting scaling, stakeholders elicitation or others (Ezell et al., 2000).

3. Risk Estimation

Risk estimation for the selected scenarios is performed based on a semi-quantitative method that uses a numerical rating scale for impact and percentages for probability and consists of the following steps:

1) Estimate the probability of occurrence for the current climate conditions and future climate scenarios.
2) Describe CIs vulnerabilities to EWEs and assess the impact of the events on the CI level.
3) Analyse the dependencies between CIs and assess the cascading effects caused by failures in CIs due to EWEs.

The risk level for the current climate conditions and future climate scenarios is calculated as:

$$\boldsymbol{Risk}_{\,current\,year} = \boldsymbol{Probability\ of\ occurrence}_{\,current\,year} * \boldsymbol{Impact}_{\,current\,year}$$

$$\boldsymbol{Risk}_{\,reference\,year} = \boldsymbol{Probability\ of\ occurrence}_{\,reference\,year} * \boldsymbol{Impact}_{\,current\,year}$$

Future scenarios for weather extremes, as obtained by climate models, can be taken into account in two ways: either by considering the increase in probability or frequency of occurrence of a hazard with a specific intensity, or the increase in intensity of a hazard with a specific probability or frequency of occurrence. In this study we opted for the first approach, as existing risk and vulnerability assessments usually refer to hazards of a specific intensity. The approach assumes that the impact of a hazard of a specific intensity will be the same in the current situation and in the future reference year, if no mitigation measures are applied. Therefore, we assume that the system of CIs and its environment will remain unchanged in the future. That is a limitation of the study, since in reality both the system of CIs (human organisations, designed physical systems, etc.), as its environment (economic growth, political stability) are dynamic in nature. Moreover, the study did not consider the effect of uncertainty in future climate scenarios on the risk level.

Probability of occurrence
The probability and the magnitude of EWEs are assessed based on historical data of previous events and on information regarding future changes in weather extremes provided by climate and weather experts and on hazards maps developed by Deltares.

Impact assessment on the CI level
To assess the impact of EWEs on the CI level, we firstly identify CIs vulnerabilities to EWEs in terms of exposure, susceptibility and resilience and then we assess the impact that results from those vulnerabilities against the following criteria or dimensions:

i. **Direct damages**: The costs associated with physical damages to assets caused during the actual event (e.g. costs for repair).
ii. **Safety loss:** The impact on the infrastructure users during and after the actual event and it can range from material damages to casualties.
iii. **Business continuity costs:** The costs due to products, services and operations affected by direct damage and disruption to the infrastructure during and after the actual event.
iv. **Environmental impact:** The impact of the event on the natural environment caused by direct damage on the infrastructure.
v. **Reputation loss:** The dissatisfaction and reputation loss for the infrastructure operator because of no, insufficient, or inadequate actions to anticipate and manage the event.

Those criteria were determined based on existing risk assessment frameworks like RIMAROCC (Bles, et. al., 2010) and after consultation with the stakeholders (Bles, Stoorvogel, Kiel, 2016) and are in line with the criteria provided by the European Commission for CI assessments, (EC COM(2006) 787 final). Since the impact level can vary between the different CIs, a common scale is adopted for all infrastructures, so that the impact on one infrastructure is comparable to the others. The main input for the impact assessment at the infrastructure level is provided using existing vulnerability or risk assessments and expert judgement.

Analysis of dependencies between CIs and assessment of cascading effects
Despite the fact that many methods to analyse dependencies between CIs have been proposed in the recent years, if they are to be used from stakeholders should be user friendly, even when analysing complex, large systems, (Utne, Hokstad, & Vatn, 2011). The methodology described in this paper aims at CIs owners and operators and uses a simple, user friendly graph based approach to model dependencies between CIs and to assess cascading effects**.** CIs are represented as nodes and dependencies as arrows that connect the nodes; on each arrow is indicated the type of the dependency (physical, cyber or logical) and a short description of the dependency. Each dependency is quantified using the impact $I_{i,\,j}$ on a Likert scale and the likelihood $L_{i,j}$, as a percentage, of a disruption being realized to infrastructure CI_j due to its dependency on CI_i, following the approach developed by Theoharidou, Kotzinikolalou, & Gritzalis (2011) and Kotzinikolalou, Theoharidou & Gritzalis (2013). Cascading impact is assessed against i) safety loss, ii) business continuity costs, iii) environmental impact and iv) reputation loss, so that is possible to compare it with the impact that results from the vulnerabilities of CIs. The main input for the methodology is provided by CIs owners and operators, based on the knowledge of their CIs and on existing risk assessments on the CI level. Therefore, the methodology tries to integrate existing information that currently lies within each organisation.

Combining common-cause and cascading failures
An event that is widespread can lead to common cause failures in multiple CIs that can in turn lead to multiple cascading failures at the same time. Although that such an event can result to very high impact, the combination of common cause and cascading failures has received limited attention in the literature. Kotzinikolalou, Theoharidou & Gritzalis (2013) extended their methodology to assess the

overall risk of combined common cause and cascading failures, by examining each CI as a route of cascading risks chains and multiplying the sum of all the possible cascading risk chains with the likelihood of the initiating event. However, the approach does not take into account that the initiating event will influence the state of operation of multiple CIs at the same time and that the dependencies between the CIs are different depending on their operational state. The approach proposed in this paper considers how the initiating EWE will affect the state of operation multiple CIs at the same time, and examines how the recovery times of the different CIs influence the cascading effects. The approach is described in detail and its application is demonstrated in a real case scenario later in the paper (Section 4.4).

4 Case study: the system of CIs of the Port of Rotterdam area

The case study was selected as an appropriate research strategy to conduct the analysis, as risk assessments of CIs to EWEs are highly contextual (Chhetri, et al., 2013). According to Eisenhardt, (1989), "theory developed from case study research is likely to have important strengths like novelty, testability and empirical validity, which arise from the intimate linkage with empirical evidence". The INTACT-case studies and their outcomes are designed to bring added value for the concerned stakeholders locally and demonstrate the validity and applicability of the INTACT approach at the broader (European) scale (van Ruiten, Bles & Kiel, 2016). Being the largest Port of Europe, the Port of Rotterdam in the Netherlands forms a good case study to analyse the risks of various EWEs for CIs, due to its location in a delta area, near the sea and major rivers and its economic importance (Bles & Stoorvogel, 2015). Seaports and their surrounding area are more likely to be exposed EWEs due to their coastal location, (Chhetri, et al., 2013); much of the damage from natural disasters the last decades has been concentrated on the coasts, (Costanza & Farley, 2007).

4.1 Data collection

In total 3 workshops and 25 interviews with representatives of 12 organisations were conducted in order to collect data about personal experiences of CIs owners, operators and risk managers regarding former decision-making situations, earlier EWEs and their impacts on infrastructures, as they are considered the most beneficial source of information ("INTACT_Wiki", 2017). The interviews were conducted in 3 phases; during the first two phases we collected qualitative information regarding the CI systems, their vulnerabilities to EWEs, as well as the dependencies between them. During the third and last phase CIs owners and operators subjectively ranked the impact of EWEs and of failures in other CIs on their system. The data acquired from the interviews and the workshops were supplemented by existing risk and vulnerability assessments on the CI level and information collected from the websites of the organisations. Finally, climate and weather data regarding EWEs were provided by climate and weather experts and by using existing hazard maps.

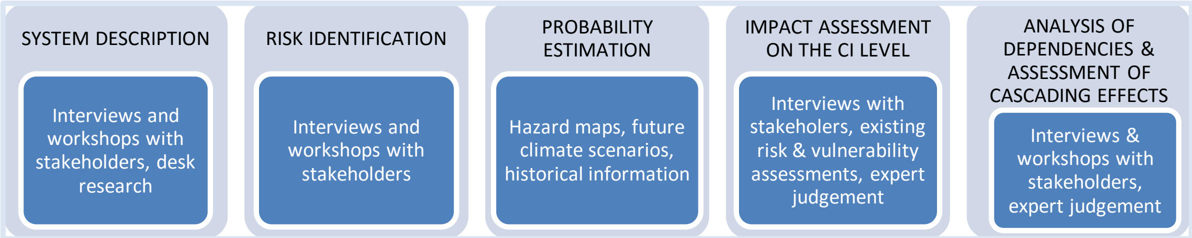


Figure 3 Data collection

4.2 System description

The Port of Rotterdam is located in a delta area, near the sea and major rivers and it is the largest port in Europe with an annual throughput of 465 million tonnes. The Port of Rotterdam area is the largest industrial cluster of Europe and employs in total something more than 180.000 people; its contribution to the gross national product of the Netherlands is estimated to be around 3 percent, ("Jaarverslagen", 2017). The total length of the port area is 42 km and it includes 12,500 ha (land and water, of which approx. 6,000 ha are business sites). The Port area is divided in smaller subareas or clusters that are commonly recognised as functional units named: Maasvlakte, Europoort, Botlek, Vondelingenplaat and Eemhaven/Waalhaven, (Figure 4). The division in clusters is based in various criteria like topography, main type of activity, period of establishment and organizational aspects, ("Rotterdam - Risk Assessment - Deltares Public Wiki", 2017). In Figure can be seen the classification used in this study as derived from the Port of Rotterdam website, ("Port of Rotterdam", 2017).

Figure 4 Map of the Port of Rotterdam area, ("OpenStreetMap", 2017)

The port of Rotterdam area includes multiple infrastructure networks that belong to the following CI sectors: Energy, ICT/Telecommunications, Transport and Chemical. The following section gives an overview of the CIs involved in the case study (Bles, Stoorvogel, Kiel, 2016).

Port infrastructure: The Port infrastructure consists of the following subsystems that facilitate the main operations of the Port and include multiple physical assets:

i. Nautical services & communication
ii. Cargo handling, storage and distribution
iii. Petro-Chemical and Energy Industry

The Port of Rotterdam Authority is the owner/landlord of the location and it manages, operates and develops the port and the industrial area of Rotterdam. The shareholders of the Port of Rotterdam Authority are the Municipality of Rotterdam and the Dutch Government. The Harbour Master division of the Port of Rotterdam Authority is responsible for handling shipping and controlling vessel traffic. Moreover, there are hundreds of private companies that provide nautical services and cargo operations services and more than 120 industrial companies in the area. Deltalinqs presents the interest of over 95% of all private companies in the main port Rotterdam.

Electricity supply: The electricity supply network is divided, in high voltage, mid voltage and low voltage network**,** based on the electric power[1] that is distributed to the end users and includes power production plants, transformer stations, distribution stations, street cabinets and the power grid. The power grid consists of the transmission grid and the local distribution grid and includes overhead lines and underground cables. The high voltage network in the Netherlands is operated and managed by Tennet, while the mid and low voltage networks in the Port area are operated and managed by Stedin. The network in each subarea or cluster of the Port area functions as an "island", therefore it is isolated from the network in the other subareas.

[1] Low voltage: 400V (volt), Mid voltage: 10-50Kv, High voltage: >150Kv

Telecommunication: The telecommunication network involves the fixed and mobile (GSM[2]) network that provides voice and data communication and includes data centres, metro core locations, cable distributors, street cabinets, radio masts and fiber cables. The telecommunication network in the Port area is manly operated and managed by KPN and Vodafone.

Hinterland transport

The extensive hinterland transportation network of the Port area connects the Port of Rotterdam to the rest of Europe and involves the following infrastructure networks:

Roads: The roads network enables people and freight transport from and to the Port and consists of the highway A15, the main provincial roads and smaller local roads and their associated elements like bridges, tunnels, viaducts, traffic management systems and electrical equipment. The A15 is the main artery in the area runs and it runs from Maasvlakte through the whole port area; it connects the Port with the national and European motorway network, therefore it is a very important element of the hinterland transport network. The A15 is operated and managed by Rijkswaterstaat[3], while the national and local roads are operated and managed by the Province of Zuid Holland, the Municipality of Rotterdam or the Port Authority. Several private transport companies provide road transport services for the Port area. Around 7.500.000 trucks visit the Port every year, ("Port of Rotterdam", 2017).

Railways: The railways network enables freight transport between the Port area and many destinations in Europe and includes subsystems like bridges, traffic control and management systems and multiple elements, such as trucks, overheadlines, power buildings and electrical equipment. The main railway line in the Port area runs parallel to A15 and is the part of the Betuwe route that connects the Port area directly with the German railway network. Betuwe route is operated and managed by Prorail, while DBSchenker is the main responsible organisation for providing freight transport services from and to Germany.

Inland Waterways: The inland waterways network of the Port area connects the Port to the rest of the Netherlands and Central Europe via the Maas and the Rhine rivers and consists of five main waterways: the Nieuwe Waterweg, the Calandkanaal, the Beerkanaal, the Hartelkanaal and the Oude Maas; waterways assets include storm surge barriers, moveable bridges, locks and traffic management systems. Around 110,000 inland vessels visit the port of Rotterdam every year, ("Port of Rotterdam", 2017). The inland waterways are operated and managed by Rijkswaterstaat, while there are multiple private companies that provide inland shipping services for the Port area. CBRB is the leading employers' organization that represents the interests of all sectors involved in inland shipping.

Pipelines: The port of Rotterdam has an extensive network of approximately 1,500 kilometers of pipelines that transports liquid bulk such as crude oil and oil products. The main pipeline corridor of the Port connects the petrochemical and energy companies in the Port area to major destinations in the Netherlands, Belgium and Germany, while there are pipelines that connect the port companies themselves. The Port Authority owns the ground and the civil works of the pipeline corridor within the Port area and is responsible for its exploitation and management. The pipelines themselves and the associated devices like pumps and valves are owned and managed by the private companies in the Port.

4.3 Risk identification

The first phase of the case study was performed by Deltares and involved the problem exploration and a preliminary risk analysis (Bles, Stoorvogel, Kiel, 2016). The relevant CIs included in the case study were selected and the stakeholders were mapped by conducting interviews with the relevant organisations. As a result of the interviews, vulnerabilities of CIs to different EW types were identified. The preliminary risk analysis was conducted during a workshop organised by Deltares; the results of the interviews were presented to the stakeholders and an inventory of cascading effects

[2] GSM: Global System for Mobile Communications

[3] Rijkswaterstaat: Part of the Dutch Ministry of Infrastructure and the Environment

caused by EWEs affecting the CIs of the Port of Rotterdam was created. Cascading effects were identified by using *CIrcle,* an interactive touch table application. The analysis was facilitated using acceleration room software, allowing input of all participants with parallel and independent brainstorming and scoring. The hazards that are relevant to CIs were identified by ranking the list of EW types deduced by the interviews. From the analysis it came out that storm, followed by extreme heavy rainfall and snow are perceived as the most important weather types that can affect the Port of Rotterdam area. The main hazards that can be induced from those weather types were identified as: i) Coastal and fluvial flooding, ii) Extreme wind speed and iii) Pluvial flooding due to extreme precipitation, (Bles, Stoorvogel, Kiel, 2016).

4.3.1 Selection of risk scenarios

The scenarios produced from the first phase of the study were further limited to a set for detailed risk analysis, through interviews with stakeholders and by studying existing risk and vulnerability assessments. In the following section is given an overview of the scenarios selected for detailed risk analysis.

Inundation of Botlek area due to Coastal Flooding

The Port of Rotterdam area is located at the Rhine–Meuse–Scheldt delta and part of the port (Maasvlakte) is directly located at the sea. The area is classified as outside the dikes, therefore there is no legal protection framework for it. Climate change and the induced sea level rise and excessive river discharge will increase the risk of coastal flooding and of fluvial flooding, respectively. Only the newest part of the Port, Maasvlakte 2 that is the extension of Maasvlakte, was built climate proof; therefore there is a good reason to examine the risks of flooding for the area for the current and the future climate conditions. Deltares used flow models in order to calculate the probability of flooding and inundation levels for the Port area, based on the current climate conditions and future climate scenarios, (Wagenaar & de Jong, 2013; Slootjes & Wagenaar, 2015). From the studies it came out that the inundation of the Port area has currently a relative small probability of occurrence and that the coastal and fluvial flood return periods are comparable to the normative flood return periods for the inside the dikes areas (typically 1.250 to 10.000 years). However, this probability will increase in the future due to climate change. Moreover, it came out that Botlek is the most vulnerable area to flooding; the exposure of the area to coastal flooding in combination with the economic importance, the type of the activities and the presence of CIs in the area, make flooding of Botlek a representative scenario to consider for further detailed analysis.

The Netherlands is quite specialized and experienced flood protection. In case of flooding in the Port area, Rijkswaterstaat will issue an early warning to other water authorities and emergency services; the warning time horizon is 36 to 48 hours. If the event is extreme and the risk level is high, the Port area will be evacuated for safety reasons.

Wind speed stronger than 7 Beaufort (Bft)

Another effect of stormy weather is strong winds that may not lead to storm surge but are still hazardous for the CIs of the Port area and therefore specific safety regulations apply. From the interviews and the workshops it resulted that specific types of sea vessels are not allowed to enter the Port when the wind in the area is blowing more than 7 Bft or even 6 Bft; moreover there can be problems with the embarkation of pilots on seagoing vessels and as a result with the navigation of the sea vessels in the port. Cranes in the Port, as well as moveable bridges are not operable for winds of Beaufort scale 7 to 8. Furthermore, wind can slow down road traffic and lead to traffic jams and accidents and cause branches of trees to fall on the railway track, therefore disturb rail traffic. Direct damages to CIs assets due to wind are minor, since most assets are designed to withstand winds of Beaufort scale 12, therefore CIs return to normal operation conditions almost immediately after the event. Smits, Klein Tank and Können, (2005) calculated that strong wind events in the Netherlands (corresponding with 19-20 m/s (8 Bft) along the coast and 16-17 m/s (7 Bft) inland) occur on average twice a year. According to KNMI[4], there is no evidence for increase in wind extremes due to climate

[4] KNMI: Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)

change, while the average Euro-CORDEX[5] climate simulations project a decrement of 2-4% in the intensity of maximum daily wind speed for the Port of Rotterdam area, over the period 2011 – 2100, (Mercogliano & Gutierrez, 2016).

Pluvial flooding due to Extreme precipitation

From the interviews and the workshop it came out that CIs owners and operators consider extreme precipitation threatening for CIs. Extreme precipitation can lead to pluvial flooding and induce risks for the Port of Rotterdam area. The water depth will be lower than in the case of coastal or fluvial flooding; however all the port areas run the risk of pluvial flooding and all CIs can be affected by it, since precipitation falls everywhere in the area. It is quite difficult to indicate when extreme precipitation will cause problems to the CIs in the port area and the extent of the problems, since the risk of pluvial flooding depends on the intensity and duration of the precipitation event, the capacity of the local drainage system, the local ground elevation and infiltration capacity, as well as on the location and altitude of the CI assets; therefore, it is a rather local phenomenon. Both KNMI and the Euro-CORDEX climate simulations project a significant increment of more than 40% in the intensity of daily and weekly precipitation for the Port of Rotterdam area, over the period 2011 – 2100, (Mercogliano & Gutierrez, 2016).

4.4 Risk analysis

For this paper, it was selected to present the detailed risk analysis for inundation of Botlek due to coastal flooding with return period 1:1000 and 1:10000 per year, as it is the scenario with the highest consequences for the Port of Rotterdam area, as well as the results of the analysis for the extreme wind speed scenario.

4.4.1 Inundation of Botlek area due to Coastal Flooding

Botlek is an industrial area of great economic importance in the Port of Rotterdam area that was built between 1940 and 1970. Botlek is bounded by four waterways, the Oude Maas, the Neuwe Waterweg, Hartelkanaal and Calandkanaal and is in open connection with the sea by Hartelkanaal, Calandkanaal and Nieuwe Waterweg. The elevation of the ground in Botlek is approximately +4.5 m and +5.0 m NAP [6] and increases from the east to the west. Moreover, there are a number of lower lying areas and underpasses on the trajectory of Europoortkering/A15. Based on the studies performed by Wagenaar & de Jong, (2013) and Slootjes & Wagenaar, (2015), flood risk for the Botlek area originates mainly from the sea, since the river flow has almost no influence. Coastal flooding of Botlek can occur due to a combination of a storm at the sea that is accompanied by extreme winds and of high spring tide. Moreover, the studies took into account the effect of seiches and waves. A seiche is an oscillation of the body of water in a (semi) closed basin, such as a port (De Jong, 2004).

Climate change is taken into account by considering the KNMI’ 14 climate scenarios for the Netherlands, (KNMI, 2014). KNMI developed four climate scenarios that differ in the amount of global warming (Moderate or Warm) or possible changes in the air circulation pattern (Low or High) and provide a consistent picture of the changes in 12 climate variables, including temperature, precipitation and sea level, (Low or High), (Table 1). KNMI found no evidence for a possible change in the wind extremes; therefore it was assumed that wind extremes will not change. Wagenaar & de Jong, (2013) and Slootjes and Wagenaar, (2015), calculated the inundation depth of Botlek for the reference year 2100 and the normative flood return periods 1:1000 per year and 1:10000 per year respectively, based on the worst case climate scenario W_H that corresponds to fast rate of climate change; the studies assumed a sea level rise of 0, 85 m in 2100. Based on the calculated inundation depth, the new return periods for the reference year 2100 were calculated as:

$$\boldsymbol{Return\ period}_{2100} = \boldsymbol{Return\ period}_{2015} * \mathbf{10}^{\frac{height\_difference}{decimeringshoogte}}$$

[5] Euro-CORDEX: COordinated Regional climate Downscaling Experiment for the European domain

[6]NAP: *Normaal Amsterdams Peil* – A vertical datum in use in large parts of Western Europe

,where decimeringshoogte denotes the “absolute height difference between the inundation depth in the current situation and the inundation depth for a factor 10 exceedance probability” and height_difference denotes the absolute height difference between the water depth for the current year and the water depth for the reference year, ("Zeeweringen - DeltaExpertise", 2017). Basically this assumes that the flooding depth increases linearly with a logarithmic scale for the return periods. From Table 2 we can see that the flood return period will decrease from 1:1000 and 1:10000 per year to 1:55 and 1:550 per year respectively in 2100.

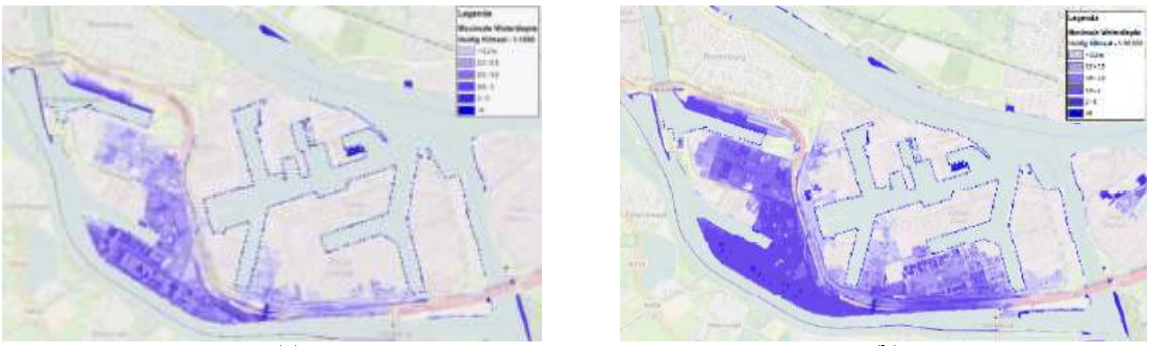
Table 1 KMNI Climate scenarios for the Netherlands, (KNMI, 2014)

Variabele	Indicator	Climate 1981-2010	Scenario changes for the climate around 2050				Scenario changes for the climate around 2085				Natural variations averaged over 30 years
			G_L	G_H	W_L	W_H	G_L	G_H	W_L	W_H	
Global temperature rise:			+1 °C	+1 °C	+2 °C	+2 °C	+1.5 °C	+1.5 °C	+3.5 °C	+3.5 °C	
Change in air circulation pattern:			low value	high value	low value	high value	low value	high value	low value	high value	
Sea level at North Sea coast	absolute level	3 cm above NAP	+15 to +30 cm	+15 to +30 cm	+20 to +40 cm	+20 to +40 cm	+25 to +60 cm	+25 to +60 cm	+45 to +80 cm	+45 to +80 cm	±1.4 cm
	rate of change	2.0 mm/yr.	+1 to +5.5 mm/yr.	+1 to +5.5 mm/yr.	+3.5 to +7.5 mm/yr.	+3.5 to +7.5 mm/yr.	+1 to +7.5 mm/yr.	+1 to +7.5 mm/yr.	+4 to +10.5 mm/yr.	+4 to +10.5 mm/yr.	±1.4 mm/yr.
Temperature	mean	10.1 °C	+1.0 °C	+1.4 °C	+2.0 °C	+2.3 °C	+1.3 °C	+1.7 °C	+3.3 °C	+3.7 °C	±0.16 °C
Precipitation	mean amount	851 mm	+4 %	+2.5 %	+5.5 %	+5 %	+5 %	+5 %	+7 %	+7 %	±4.2 %
Solar radiation	solar radiation	354 kJ/cm²	+0.6 %	+1.6 %	-0.8 %	+1.2 %	-0.5 %	+1.1 %	-0.9 %	+1.4 %	±1.6 %

Table 2 Return periods of coastal flooding for Botlek, under the current and the future climate conditions

Scenario: KNMI W^+-2100 (fast climate change, +0,85 m)	Current return period (2015)	Reference return period (2100)
	1:1000 per year	1:55 per year
	1:10000 per year	1:550 per year

Figure 5a and 5b show the inundation depths in Botlek for the two examined coastal flooding return periods, under the current climate conditions. In case of coastal flooding with return period 1:1000 per year, mainly the Southwest part of Botlek will be overflowed and the water depth will be up to 2.0 m; the area east of A15 and Betuwe Route is hardly flooded. In case of coastal flooding with return period 1:10000 per year, the inundation depth and the extent of the area that is overflowed increase, as the conditions become more extreme. The part east of A15 and Betuwe Route is flooded as well and the water depth will be up to 1.0 m and in some locations even up to 2.0 m, (Slootjes & Wagenaar, 2015).The duration of the events is limited (24h to 36 hours) and the flow rate is relatively low.



(a) (b)

Figure 5 Inundation depths in Botlek for Coastal flooding with return period: (a) 1:1000 per year, (b) 1:10000 per year (current climate conditions)

Impact assessment on the CI level

Botlek, as the whole Port of Rotterdam area, includes multiple CIs that are vulnerable to flooding. The impact of coastal flooding on the CI level due to CI vulnerabilities is assessed against various criteria. From the preliminary risk analysis it came out that each impact criterion has a different relative importance, therefore it is assigned a different weight (Bles, Stoorvogel, Kiel, 2016). The total impact is calculated as the weighted average of the different criteria indicators. The criteria used for the impact assessment and the assigned weights are represented in Figure 6.

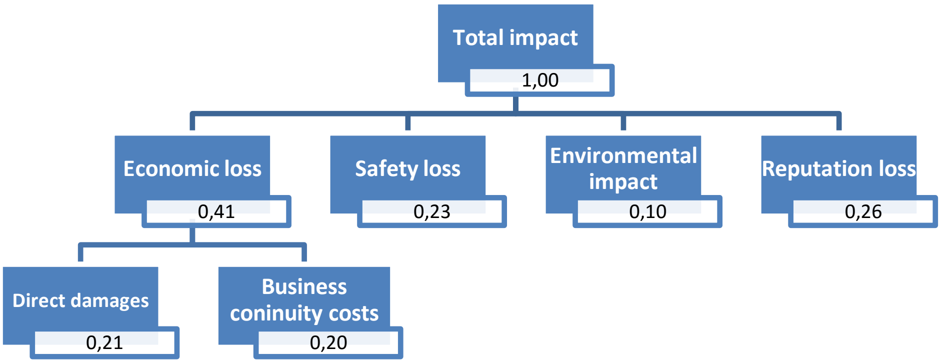


Figure 6 Impact criteria and assigned weights

Economic loss is considered the most important impact dimension, followed by reputation loss and safety loss. Reputation loss is considered quite important because it can lead to market share reduction for the Port area. Impact is assessed on a Likert scale that is common for all the infrastructures. The scales are constructed based on RIMMAROC risk assessment framework (Bles, et. al., 2010) and after consultation with the stakeholders. Table 3 describes the impact scales used for the assessment.

Table 3 Impact indicators and scales

			Impact scale		
Impact criteria	1	2	3	4	5
Reputation loss	Negligible loss of reputation	Slight loss of reputation (complaints)	Moderate loss of reputation (notices on media)	Significant loss of reputation (attention in national wide politics)	Severe loss of reputation, position of minister at stake
Safety loss	Only material damages	Minor injuries	Heavy injuries	Casualties	Several casualties
Direct costs (€)	<100.000	100.000 - 1 million	1 million - 10 million	10 - 100 million	> 100 million
Business continuity costs (€)	<100.000	100.000 - 1 million	1 million - 10 million	10 - 100 million	> 100 million
Environmental impact	Negligible impact on the directly surrounding infrastructure environment	Slight impact on the nearby surrounding infrastructure environment	Moderate impact on the nearby surrounding infrastructure environment	Significant impact on the on the environment in the wider infrastructure area	Severe impact on the environment in the wider infrastructure area

CIs vulnerabilities to flooding

Botlek, as the whole Port area, includes multiple CIs. Below is given an overview of the vulnerabilities of the CIs of Botlek to the examined coastal flooding events.

<u>Port Infrastructure</u>: Multiple Port Infrastructure assets in Botlek are exposed to coastal flooding; the susceptibility degree depends on the water depth and on the location and type of the CIs assets. Moreover, many of the petrochemical and energy companies are interconnected; therefore if the operation of one company is interrupted the other companies will be affected as well. It was estimated that it will take between some months to one year for the Port Infrastructure to recover from flooding; however, it was difficult for the stakeholders to indicate the exact recovery duration, as it depends on multiple factors and they do not have previous experience with so extreme events.

<u>Electricity supply</u>: the presence of water is damaging for electricity supply assets, since it can lead to corrosion and short circuits. In case of an asset failure, electricity supply through the asset shuts down;

failures of small distribution stations and street cabinets can be isolated within some hours. The high and mid voltage networks operate on redundancy, while low voltage network has no redundancy. Electricity operators may preventively shut down electricity supply based on safety procedures, in order to avoid short circuits. From the interviews with electricity operators it came out that the high voltage network will not be affected in any of the two examined flooding events; mid and low voltage networks on the other hand will be affected by both events

Telecommunication: Telecommunication assets are susceptible to flooding, since the presence of water can lead to short circuits. In case of failure the mobile network can run on emergency power for 2 hours. The exact effect of coastal flooding on fixed and mobile network of Botlek, as well as the recovery time are not exactly known. Nevertheless, it is expected that that there will be outages of both networks and that telecommunication services will be interrupted. For the recovery time it was assumed that it will be at least as long as that of electricity assets (6 weeks to 2 months).

Roads: A15 in Botlek lies on the top of Europoortkering and due to its low elevation it is exposed to coastal flooding at multiple locations. The length of the overflowed part as well as the water depth increases with the flooding return period, (Figure 5a & 5b). A15 embankments are susceptible to flooding and it can lead to embankment instability and in some cases collapse of sections of the road (Stoevelaar, 2014). Moreover, the water flow can cause erosion of the foundation of underpasses and lead to structural integrity problems. Electrical installations along A15 are susceptible to flooding as well, due to corrosion and short circuits. Finally, tunnels and bridges in the area are not exposed to the examined flooding events. As the conditions become more extreme it is expected that there will be problems in more locations; however, A15 is of great importance to the national economy and of high priority for repair, therefore more resources will be allocated for its repair. The recovery time of A15 can vary from some weeks, if there are instability problems but no collapse, up to 3 or 4 months if sections of the road collapse, depending on the total length of the sections.

Railways: The main railway of Botlek is part of Betuwe Route, runs parallel to A15 and is exposed to coastal flooding at multiple locations. The presence of water in the rail system is damaging for the multiple electrical installations; when the water depth on the track exceeds 25 cm the system falls out and no trains can run anymore. Moreover, railway embankments are susceptible to flooding and it can lead to instability and maybe collapse; the exact effect on the stability of embankments is not known. It was assumed that the recovery time of Betuwe route will be at least as long as that of Roads, as railway embankments are much smaller than highway embankments but railways include multiple electrical sub systems and installations that need to be repaired.

Inland waterways: The inland waterways system is quite robust to flooding and problems can occur only if the electrical installations of the bridges are damaged or the water level is too high for vessels to pass under certain bridges. However, the bridges in the Port area are highly elevated and they will not be affected by the examined flooding events.

Pipelines: Pipelines themselves are quite robust to EW hazards like flooding. The only susceptibility of the system is with regard to electrical installations and ICT control systems that can be damaged by the presence of water. However, the transportation from and to the Port area through Botlek will not be affected, as it is anticipated that pipelines owners will have enough time before the event to turn off their connections with the main pipeline corridor.

As the recovery time of A15 and Betuwe route is uncertain, it was decided to examine the impact of coastal flooding on Roads and Railways for the two following recovery scenarios. In the **1st recovery scenario** it is assumed that sections of A15 and of Betuwe Route will collapse and it will take 3 to 4 months to recover; electricity assets and telecommunication assets will be the first to recover from flooding, 2 months after the event. In the **2nd recovery scenario** it is assumed that roads and rail are less heavily damaged than in the 1st scenario and that A15 and Betuwe Route will recover one month after the event, therefore before electricity and telecommunication. The recovery time of electricity and telecommunication assets depends on the availability of A15; therefore it will be shorter than in the 1st scenario. However, it was conservatively assumed that it will take 2 months, as in the 1st scenario.

Figure 7a and 7b present relative indications of the impact level on each CI due to vulnerabilities of CIs to coastal flooding of Botlek with return period 1:1000 per year and 1:10000 per year respectively, under the current climate conditions and for the two examined recovery scenarios. The impact level indicates the maximum impact level produced for each CI during a period of 2 months after the flood event, assuming that the Port area will be evacuated for safety reasons. From the figures it can be seen that the impact of the 1:10000 per year coastal flood event is slightly higher in comparison to the 1:1000 per year event, for all the CIs except for Inland waterways and Pipelines. That is due to the fact that inland waterways and transport via the Pipelines are quite robust to flooding; the resulted impact refers mainly to business costs, as the Port area will be evacuated for safety reasons and the operation of all CIs will be shut down for 3 days. The impact on Roads and Railways is higher in case of recovery scenario 1 (assuming that A15 and Betuwe route are heavily damaged and electricity assets recovers first), while for Mid & Low voltage network is higher in case of recovery scenario 2 (assuming that Roads and Railways recover first). That is due to the fact that the end users of Electricity supply are the other CIs and they exhibit limited dependency on Mid & Low voltage networks when they are under recovery. Unfortunately there was not enough data available to assess the impact of flooding on telecommunication networks.

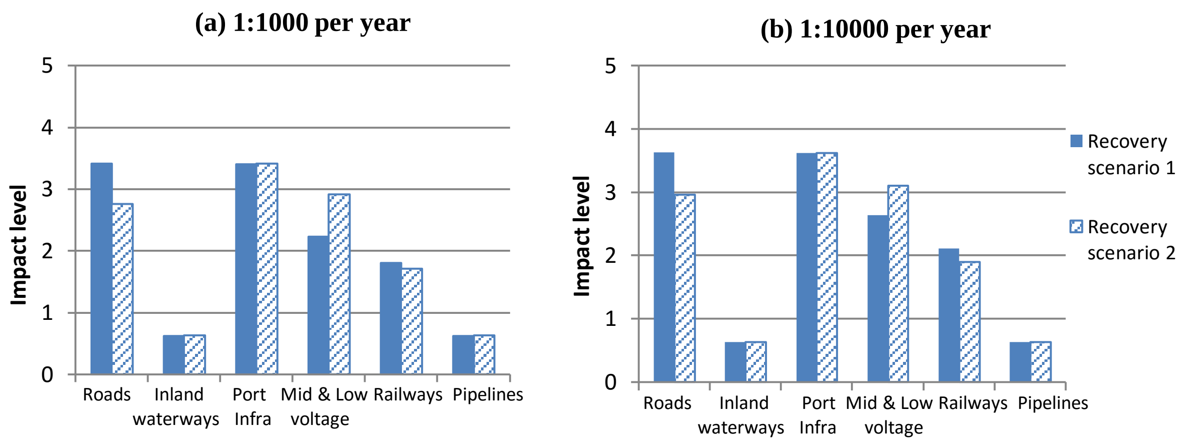


Figure 7 Impact on CIs due to vulnerability to coastal flooding with return period: (a) 1:1000 per year, (b) 1:10000 per year (current climate conditions)

The main impact of flooding on Port Infrastructure will be with respect to reputation loss and economic loss. Direct costs will be excessively high both for the 1:1000 per year and the 1:10000 per year flooding events. Business continuity costs increase as the flood return period decreases and the event becomes more extreme, since the direct damages to assets will be more extensive and it will take longer to return to normal operation conditions. Moreover, it is likely that there will be damage to the natural environment, because many of the companies in the area store large quantities of hazardous substances that are toxic, flammable or explosive ("Risicokaart website", 2017); the main environmental risk is addressed as oil leak from tanks that can spread through the water surface to the wider area. Safety loss will be minor, since there will be enough time for people to evacuate the area and the petrochemical industry has regulations for shutting down production in case of EWEs. The main impact of flooding on electricity supply will be with respect to reputation loss and economic loss; direct damages will be more extensive in the case of the 1:10000 coastal flooding, as conditions become more extreme. Environmental impact is also possible because pollutants from electricity assets can release to water. Safety loss is not considered important as there will be preventive or automatic shutdown of electricity and repairement takes place only in a safe environment. The impact for the Roads operator will result mainly from direct costs and reputation loss, as the A15 is very important for the connection of the Port area with the rest of the Netherlands and it is anticipated that it will be available even under the most extreme conditions. Transport providers and other road users will suffer business costs as traffic will be retoured to smaller provincial roads around the Port area until A15 recovers. Rerouting to other roads will lead to safety loss as well, but it is expected that safety issues will decrease eventually, as users will switch to other modalities. Finally, there will be no impact to the natural environment due to damage of A15. The main impact for the railways operator will be with respect to direct costs; reputation loss is consider minor, as the responsibility for preventing the flood events falls within the Public Authorities and the Dutch government. Betuwe Route is the main railway line in the Port area and there is no alternative line; therefore transport by rail will stop until it recovers. That will lead to business costs for transport providers. Safety loss is not regarded as an issue, since the Port area will be evacuated before the flood event; moreover, there will be no environmental issues due to damage of railways.

Relevant information was collected for all the selected scenarios by interviewing CI owners and operators and was organised in tables, like Table 4.

Table 4 Example Impact assessment on the CI level for Coastal flooding of Botlek

Affected CI	Hazard	Vulnerable asset/ operation	Exposure to hazard	Susceptible elements	Susceptibility factors	Time to recover
Roads	High water levels ouside dike areas caused by coastal flooding during severe storm with probability 1:1000 (Flood Duration: 24h - 36h)	A15 - Botlek	A15 is flooded at multiple locations, in total around 2 km with 0.2 - 0.8 m water depth, locally higher	Road embankments and foundation, electrical installations and systems like out stations, underpasses, transport operations	Slope of embankments, local soil conditions, asset elevation	It depends on the extend of the damage. If A15 is heavily damaged and entire sections of the road collapse, it may take 2-3 months. If only local damages, 2 weeks to 1 month.

Effect	Impact level					
	Direct costs	Reputation loss	Safety loss	Business continuity costs	Environmental impact	Total impact
A15 is flooded. Extended stability problems, possible collapse of sections of the road, erosion of the underpass foundation, possible structural integrity problems. Traffic through A15 stops, rerouting to N218.	3	5	3	4	-	3.4

Analysis of Dependencies and assessment of cascading effects

As previously described, the Port of Rotterdam area includes multiple CIs that are highly interconnected; therefore, the failure of a CI in Botlek can cause disruptions to the other CIs not only in Botlek, but in the whole Port area. Moreover, CIs exhibit different set of dependencies depending on their state of operation. Therefore, it is very important to determine for all CIs their dependencies on other CIs for all the states of operation.

Figure 8 presents the model of the dependencies between the CIs of the Port area for the normal state of operation. CIs are modelled as nodes and dependencies as arrows that connect the nodes. The following section gives an overview of the dependencies between CIs under different operation conditions, as well as of the contingency measures taken by CIs operators in order to deal with disruptions realised on their CIs caused by failures in other CIs.

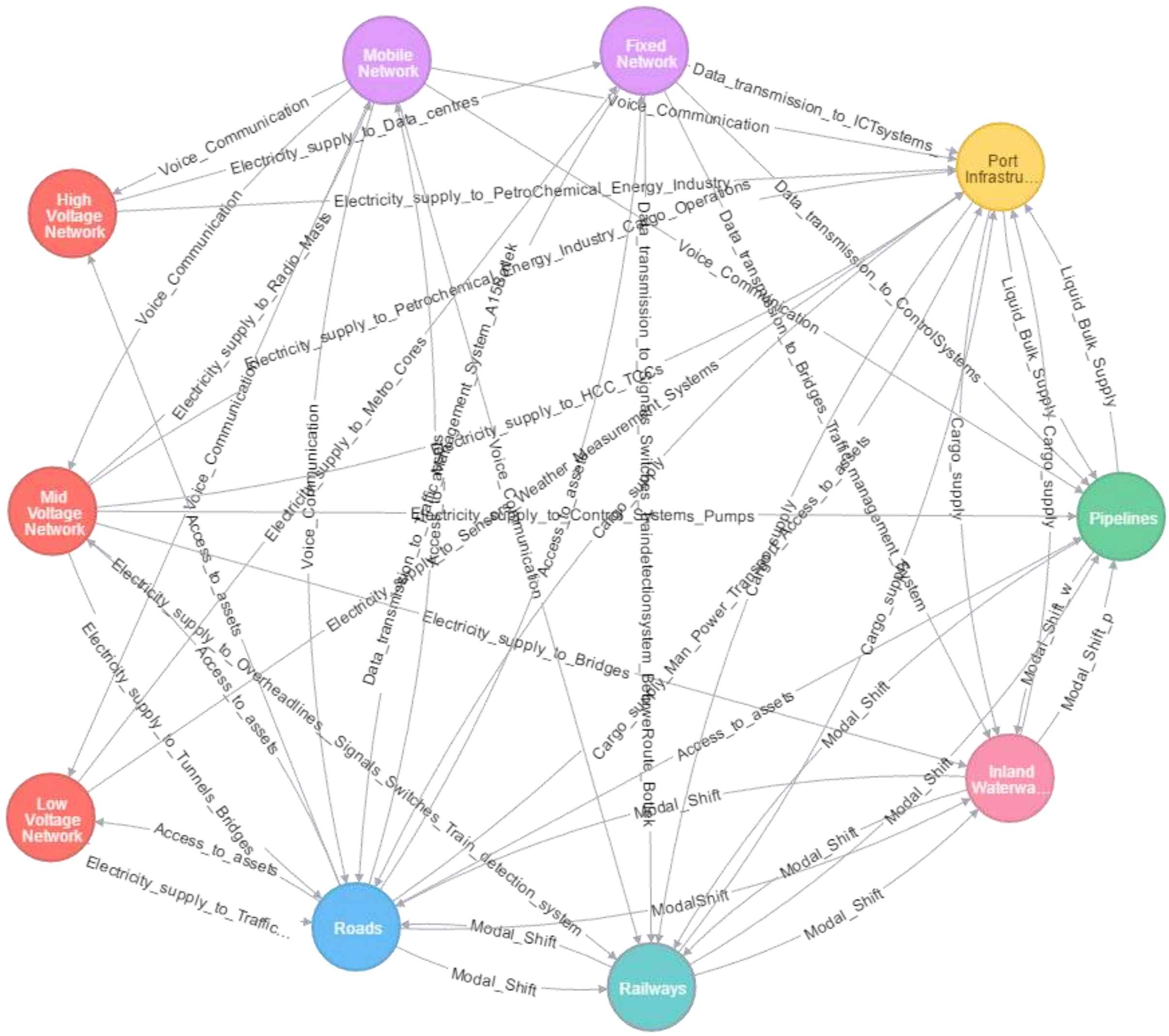


Figure 8 Dependencies between CIs of the Port of Rotterdam area under normal state of operation

Description of dependencies

From the analysis it came out that most dependencies between the CIs of the Port of Rotterdam are physical. Electricity supply is very important for all CIs, especially under normal operation conditions. In case of an outage in high voltage power supply, both Port Infrastructure and Telecommunications operations will be disrupted. Diesel generators will be used by data centres and the industrial companies of the Port for downgrading of activities. Mid voltage power seems to be of crucial importance for the functioning of most CIs.

Railways are highly dependent on mid voltage power supply for their function and in case of an outage they will run out of service. Transport providers have taken some contingency measures like extra diesel motors in their engines that can be used in case of emergency; if power outage lasts longer than some days, they may use diesel trains. Mid voltage power supply is very important also for Roads and Inland Waterways, as the function of tunnels and bridges depends on mid voltage power supply. In case of an outage there are back up power systems for the function of tunnels, while some bridges have UPS batteries for the function of lights, stops, barriers and signals; moreover, moveable bridges can be opened mechanically. Telecommunications system exhibit also dependency on mid voltage power supply for the function of radio masts; in case of a failure, the mobile network can run on emergency power up to 2 hours, while of overlap of radio masts serves as a back-up. Mid voltage power supply is very important for the Port Infrastructure operations; For example, the logistic process of the chain of goods transport from sea shipping to the distribution along the various modes of transport to inland location is highly automated. In case of an outage in mid voltage power supply there are in place diesel generators for the Harbour Coordination Centre and Traffic Control Centres, as well as UPS batteries for most radar installations. Finally, mid voltage power supply is necessary for the function of ICT control systems and pumps of Pipelines. Low voltage power supply is also important, for example for the function of the traffic management system of Roads or of the weather measurement systems of the Port.

The fixed network (fiberglass) is of crucial importance for all CIs with regard to the ability of issuing alarm notifications. Moreover, fixed network is necessary for controlling and monitoring of all ICT and traffic management systems. In case of a failure in fixed network, rail and road traffic will be managed by using personnel and non-digital signage. Mobile network is important for voice communication both under normal and emergency operation conditions for most CIs. However, the Inland waterways operators uses VHF canals for voice communication, while the Port Authority can as well use VHF communication or communication satellites in case of an outage in mobile network. Railways operators use the GSM-R [7] mobile network, therefore the dependency of railways dependency on the GSM mobile network is limited. Finally, electricity operators have their own fixed network and they can use an alternative mobile network in case of emergency.

Availability of the hinterland transport system is necessary for the constant flow of cargo from and to the Port, especially in the case of hazardous substances, as companies are allowed to store only limited amounts each time. In case that one modality is not available, users can switch to other modalities, for example rail users can switch to inland waterways or roads. A15 is very important for the accessibility to the whole Port area, both under normal and emergency operation conditions of CIs. Electricity supply and Telecommunication operators for example, depend on Roads for dispatching staff to inspect and repair damaged assets. In case that A15 is unavailable, access to the Port area will be severely disrupted but it will be still possible via other surrounding roads or via inland waterways. Transport providers depend on the cargo flow from the Port of Rotterdam for the continuity of their business. In case that Port Infrastructure operations are disrupted stakeholders expect a loss of income, claims and inability to meet obligations with regard to transportation of goods.

Cascading effects of common cause failures

Dependencies are quantified in terms of the risk or impact that the outage of one infrastructure produces for the dependent infrastructures. For simplicity reasons it is assumed that the likelihood Li, j of a disruption being realized to CIj due to its dependency on CIi, is certain, therefore equal to 1; thus the cascading risk Ri, j is equal to the cascading impact Ii, j. Impact is assessed against safety loss, business costs, environmental impact and reputation loss, using the same criteria weights as in the impact assessment due to vulnerabilities on the CI level, so it is possible to compare the results. As previously described, in case of coastal flooding of Botlek multiple infrastructure systems are going to be affected by the event that in turn will lead to multiple cascading failures at the same time. It was empirically found that the recovery time of the different CIs has an important influence on the cascading effects; moreover the level of the cascading impact depends on the duration of the disruption and it does not evolve with time in the same way for all the dependencies (Stergiopoulos et al., 2016). Table 5 presents some example dependencies between the CIs of the Port area and the associated cascading effects induced by coastal flooding of Botlek with return period 1:1000 per year, for the 2nd recovery scenario in which roads and railways recover before electricity. Cascading impact is assessed for different points in time for a period up to 2 months after the evacuation of the Port. It was assumed that cascades will start after the third day, when the Port area can be operated again. Based on the table, one can construct the respective dependency graph (Figure 9). The value associated to each dependency refers to the maximum cascading impact produced by the dependency during a period of 2 months after the evacuation of the Port area.

[7] GSM-R: international wireless communications standard for railway communication and applications

Table 5 Example cascading effects of common cause failures due to coastal flooding of Botlek with return period 1:1000 per year (current climate conditions) _ Recovery scenario 2

Source CIi	*Recovery time*	*Dependent Cij*	*Recovery time*	*Effect*	*Impact type*	*Li,j*	*Ii,j (= Ri,j)*			
							4 days	*1 week*	*1 month*	*2 months*
Mid voltage network in Botlek	2 months after the event	Pipelines	almost immediately after the event	Transportation via the main Pipeline corridor will not be affected	-	-	-	-	-	-
Mid voltage network in Botlek	2 months after the event	Railways	1 month after the event	Cascades will start after Railways recover. Betuwe route will run out of service.	Business costs	1	0	0	0	0.8
Mid voltage network in Botlek	2 months after the event	Port infrastr.	some months to 1 year	Port Infrastructure in Botlek will recover after the Mid voltage network. No cascades due to outage in Mid voltage power supply.	-	-	-	-	-	-
Roads	A15 recovers 1 month after the event	Mid & Low voltage networks	2 months after the event	Mid and low voltage networks will receive cascades from Roads only during recovery. Repair of electricity assets will be hindered.	Reputation loss, business costs	1	1.2	1.2	1.2	0

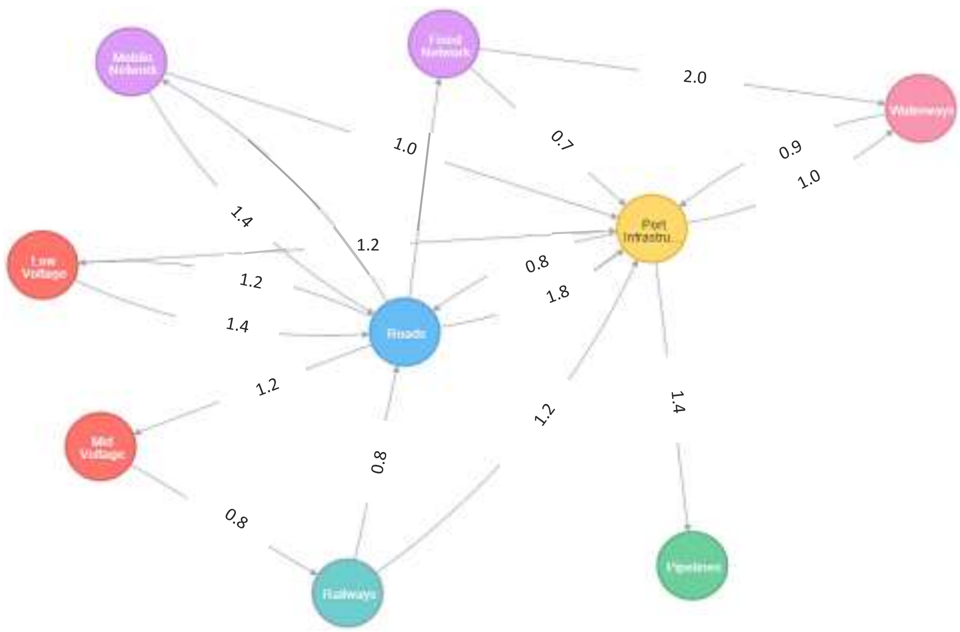


Figure 9 Dependency graph for Coastal flooding of Botlek with return period 1:1000 per year (current climate conditions) _ Recovery scenario 2

Table 6 summarises the maximum cascading impacts produced by the dependencies between CIs due to Coastal flooding of Botlek, within a period of 2 months after evacuation of the Port. It can be seen that some dependencies do not add to the total cascading impact; that is due to the fact that coastal flooding will cause common failures on multiple CIs and therefore multiple cascading failures at the same time.

Table 6 Summary of cascading impacts of common cause failures caused by Coastal flooding of Botlek

		Maximum cascading impact *Dependent Cij*							
Scenario	***Source Cii***	**Port Infrastructure**	**Roads**	**Railways**	**Inland waterways**	**Pipelines**	**Mid & low voltage network**	**Fixed network**	**Mobile network**
1:1000 per year, recovery scenario 1	**Port Infrastructure**		0,8		1	1,4			
	Roads	2,1					1,2		
	Railways	1,2	0,8						
	Pipelines								
	Inland waterways	0,9							
	Low voltage network	1,2							
	Mid voltage network								
	Fixed network	0,7			2				
	Mobile network	1	0,7				does not add		
1:1000 per year, recovery scenario 2	**Port Infrastructure**		0,8		1	1,4			
	Roads	1,8					1,2		
	Railways	1,2	0,8						
	Pipelines								
	Inland waterways	0,9							
	Low voltage network	1,2							
	Mid voltage network		0,7	0,8					
	Fixed network	0,7			2				
	Mobile network	1	1,4				does not add		
1:10000 per year, recovery scenario 1	**Port Infrastructure**		0,8		1	1,4			
	Roads	2,1					1,4		
	Railways	1,2	0,8						
	Pipelines								
	Inland waterways	0,9							
	Low voltage network	1,2			2,6				
	Mid voltage network								
	Fixed network	0,7			does not add				
	Mobile network	1	0,7				does not add		
1:10000 per year, recovery scenario 2	**Port Infrastructure**		0,8		1	1,4			
	Roads	1,8					1,4		
	Railways	1,2	0,8						
	Pipelines								
	Inland waterways	0,9							
	Low voltage network	1,2	1,8	0,8	2,6				
	Mid voltage network		0,7						
	Fixed network	0,7			does not add				
	Mobile network	1	1,4				does not add		

Figure 10 and Figure 11 present relative indications of the total cascading impact level received per day by each CI, during a period of two months after the evacuation of the Port. Due to unavailability of sufficient data it was assumed that the impact growth rate follows a linear trend; however, in reality the cascading impact does not evolve with time in the same way for all the dependencies between CIs. The cascades will start when it is safe to return back to the Port area (around 3 days after the evacuation), because during that period the CIs operations will be shut down. As some CIs receive cascading impact from more than one CI at the same time, it was assumed the total cascading impact received by each CI due to all its dependencies on other CIs is equivalent to the highest. That assumption may lead to a slight underestimation of cascading impacts; however, intangible impacts like safety loss, reputation loss and environmental impact are not easily measurable and therefore the assessment of the total impact level is subjective.

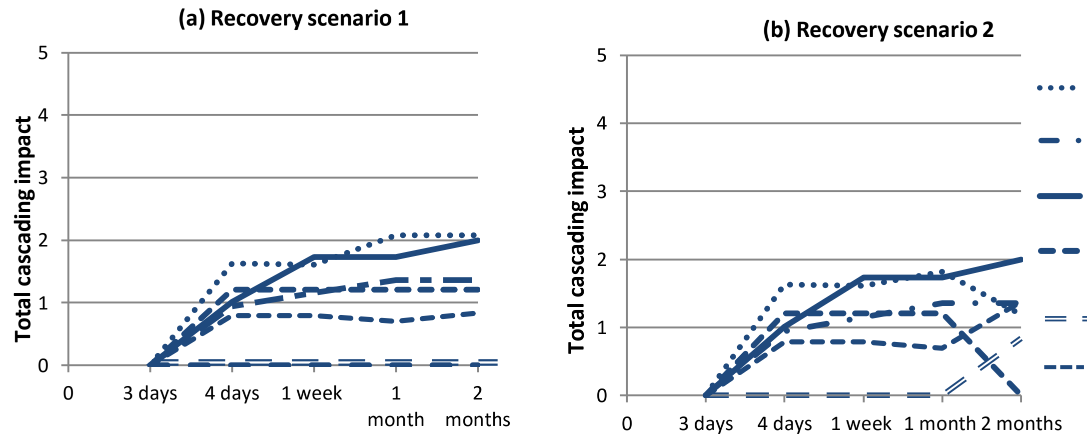


Figure 10 Total cascading impact per day received by each CI due to Coastal flooding of Botlek with return period 1:1000 per year (current climate conditions): (a) Recovery scenario 1, (b) Recovery scenario 2

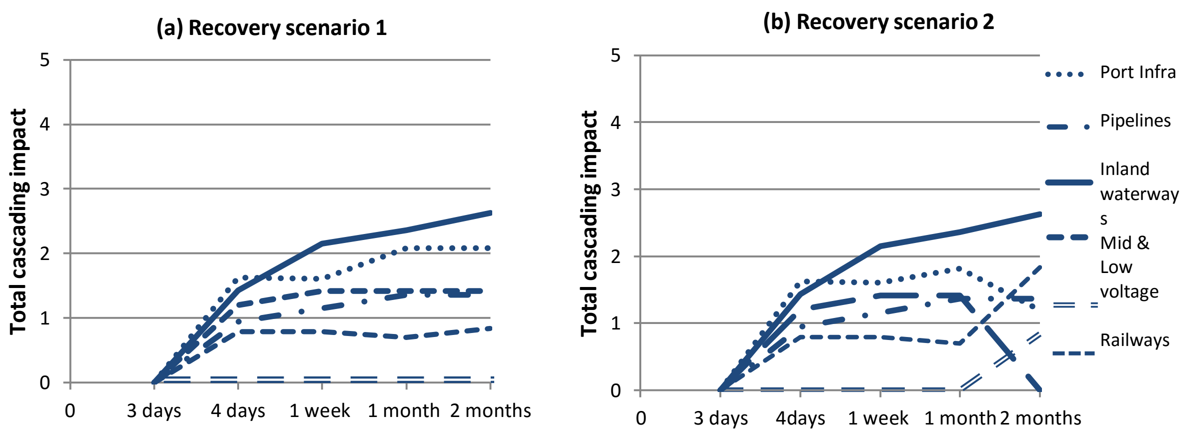


Figure 11 Total cascading impact per day received by each CI due to Coastal flooding of Botlek with return period 1:10000 per year (current climate conditions): (a) Recovery scenario 1, (b) Recovery scenario 2

From the figures it can be seen that in most scenarios Inland Waterways and Port Infrastructure will receive the greatest cascading impact. Inland waterways are quite robust to flooding and therefore they will be directly affected by the event only during the period that the Port area is evacuated. Cascading impact will mainly be with respect to reputation loss for operators and business costs for the users Inland Waterways, due to limited cargo supply from Botlek. The greatest part of the cascading impact on Port Infrastructure will be in terms of reputation loss for the operators and business costs for the users of the system and will result from the unavailability of A15 and Betuwe Route, since the accessibility to the Port areas west of Botlek that are not flooded will be hindered. Outage of Electricity supply and Telecommunications in Botlek will produce only limited cascading impact on the Port Infrastructure, since most dependent Port operations will be under recovery. The limited cargo supply from Botlek will cause business costs for Roads, Railways and Pipelines users as well. The cascading impact for Roads and Railways transport providers and users will be higher in the case of Recovery scenario 2, in which A15 and Betuwe route recover before the other CIs. Cascades for Railways will start after Betuwe Route recovers, since there is no alternative line for the Port area. Cascading impact for Roads will steeply increase after the recovery of A15, as Telecommunications services in Botlek will be limited and that can delay the response of emergency services in case of an accident and therefore lead to safety loss.

It can be seen that the recovery times of CIs will strongly influence the cascading effects and in most cases cascading impact will be higher when CIs have recovered from the EWE; however, that is not the case for Mid and Low voltage networks that depends on other CIs mainly during recovery, since most electricity and assets are remotely operated. Cascades for electricity will increase with time until A15 recovers and will zero after A15 is available to traffic again. On the other hand, the intensity of the flooding event will influence cascading effects for Inland waterways and Roads and slightly for Mid and Low voltage networks. As conditions will become more extreme, the flood will be more extensive and will affect more electricity assets in Botlek area, including the distribution stations that supply electricity to bridges and tunnels. A disruption realised in tunnels and bridges will causereputation loss for the Inland waterways and Roads operators, as well as safety loss and business costs for the users of the infrastructures. Cascading impact for electricity operators will increase due to the fact that the repair of more electricity assets will be hindered by the unavailability of Roads in the Port area.

Risk matrices

It was selected to represent the risk matrices under the current and future climate conditions for two EWEs: i) coastal flooding of Botlek with return period 1:1000 per year (current climate conditions), assuming recovery scenario 1, and ii) wind speed greater than 7 Bft with an average duration of 12 to 14 hours. Figure 12a presents risk level per CI due to CIs vulnerabilities to EWEs; Figure 12b presents the total cascading risk level received by each CI due to common cause failures induced by EWEs, while Figure 13 presents the total risk level for each CI. The total risk level per CI was estimated as the summation of the risk levels presented in Figure 12a and Figure 12b, after translating the impact level in monetary terms, based on the constructed impact scales. Risks induced by coastal flooding refer to the maximum risk level during a period of 2 months after the evacuation of the Port, while risks induced by wind speed refer to the maximum risk level during a period of 2 days. It should be noted that the estimated risk levels represent relative indications of risks and not the actual risk values. The probability of occurrence of the EWEs is presented in terms of return period on a reversed logarithmic scale. It was assumed that the return period of coastal flooding will decrease from 1:1000 to 1:55 per year and from 1:10000 to 1:550 per year for the reference year 2100, due to climate change; that means that the probability of occurrence of coastal flooding will increase around 18 times in 2100. The return period of the wind event will stay approximately the same in the future. It was assumed that the impact of the EWEs will stay the same in the current and the future reference year; that is a limitation of the study, since the environment of CIs will change by 2100, therefore the impact level will change as well.

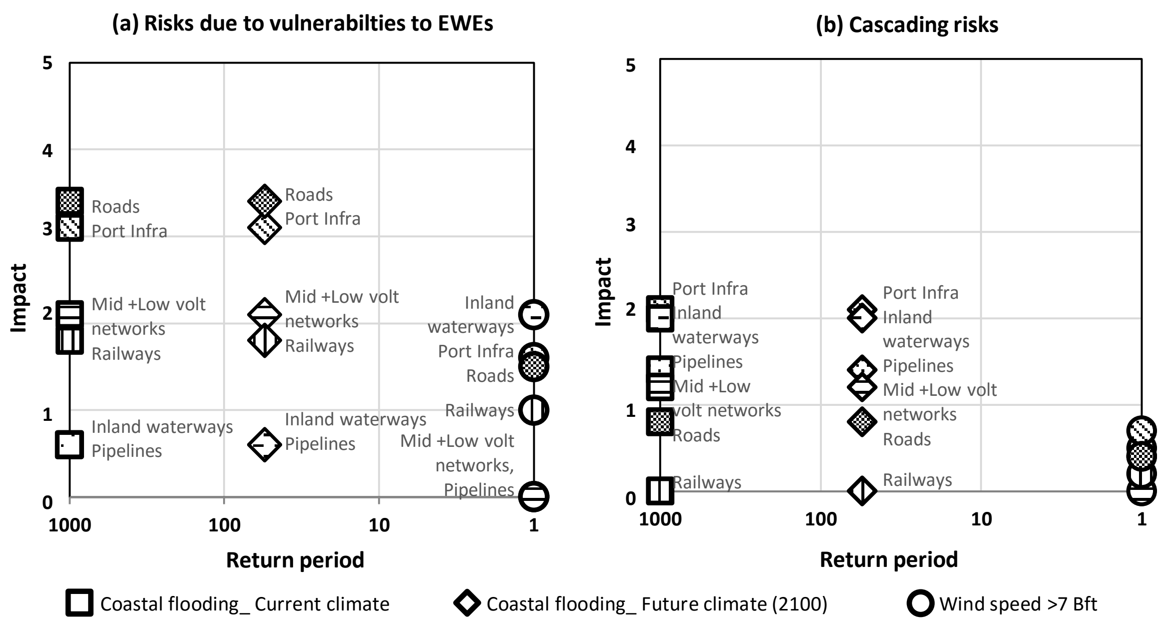


Figure 12 Risk matrices: (a) Risks due to vulnerabilities of CIs to EWEs, (b) Cascading risks

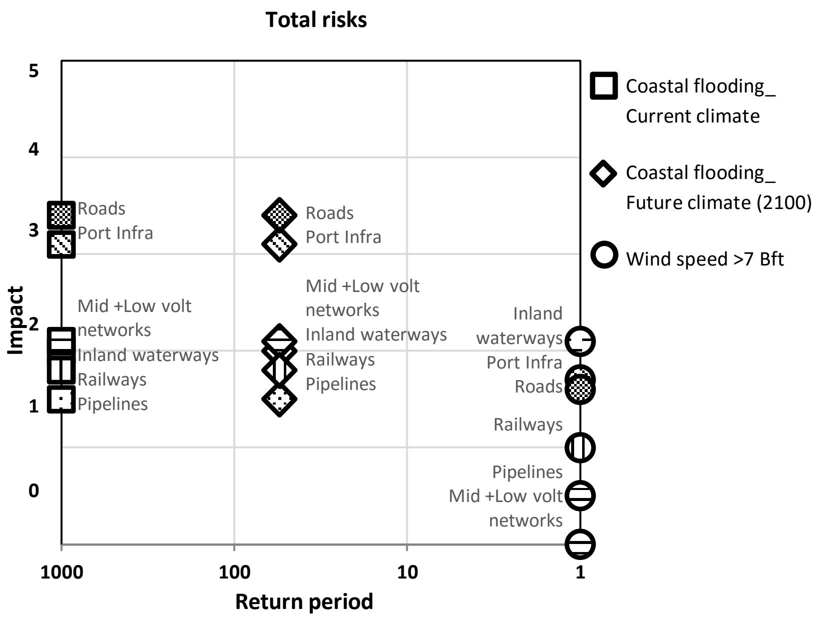


Figure 13 Risk matrix of total risks

From Figure 13 it can be seen that risks for Roads and Port Infrastructure rank high both for the wind event and the coastal flooding event (future climate scenario), while risk for Inland Waterways ranks high for the wind event. For most CIs the risks that result from CIs vulnerabilities to EWEs on the CI level will be higher than the cascading risks of common cause failures on the system of CIs level. Therefore, the greatest part of the total risk for each CI will mainly result from the direct effect of EWEs on the CI, except for Inland Waterways and Pipelines in the case of coastal flooding, as they are quite robust to that type of hazard. That is due to the fact that most CIs will be directly affected by the EWEs and as a consequence they will be under recovery for a certain period of time. From the interviews with CIs owners and operators it came out that in most cases the cascading impact received by a CI is higher when the infrastructure is not directly affected by or has recovered from the EWEs and its state of operation is influenced only by its dependency on other CIs. Regarding the different types of EWEs, the risks induced by wind speed greater than 7 Bft are of higher probability and lower consequences in comparison to coastal flooding; moreover, the probability of occurrence of wind extremes is not expected to increase in the future. However, stakeholders should account for strong wind events in their Risk management decisions, as they occur on average two times per year.

5 Discussion and conclusions

This paper describes a semi quantitative methodology to analyse risks of systems of interdependent CIs to EWEs, taking into account future climate scenarios. The methodology aims to assist CI owners and operators in risk assessment regarding EWEs and climate change and in decision making regarding risk mitigation options for their CIs. The methodology makes a clear distinction between the risks that arise from vulnerabilities to EWEs on the CI level and the risks that arise from dependencies between CIs and uses a simple, user friendly, graph based approach to analyse dependencies between CIs. The methodology was implemented in a case study, the interdependent CIs of the Port of Rotterdam area, in the context of the EU-FP7 INTACT project. The study makes an effort towards the assessment of cascading effects caused by common cause failures, as the scenario examined in detail refers to a common cause EWE that will affect multiple CIs at the same time and therefore will lead to multiple cascading failures.

From the case study it came out that, for most CIs, the risks that arise from CIs vulnerabilities to EWEs on the CI level will be higher than the cascading risks of common cause failures on the system of CIs level. Moreover, the recovery time of the different CIs from the EWEs will strongly influence the cascading effects and for most CIs the cascading impact received from other systems will increase after they recover from the EWEs. Most CIs owners and operators are aware, to some extent, of the risks of EWEs and climate change with regard to their own systems; however, they lack insight into the resilience of the systems that they are connected to, as knowledge about vulnerabilities of CIs remains within the organizations themselves. Moreover, the level of detail defers between the different organisations, as some of them have an increasing quantitative insight into their vulnerabilities regarding EWEs, while others have insight merely on a qualitatively basis. For the time being, CIs owners and operators deal with CI vulnerabilities individually, while it is not clear who is the risk owner when it comes to cascading failures.

CIs owners and operators can employ the methodology to broadly estimate how risks for their CIs will increase due to climate change. They can also use the methodology to compare the risks that arise from the CI vulnerabilities to EWEs with the risks due to dependencies on other CIs, in order to raise their awareness of systemic risks; moreover, they can identify critical elements of the overall system of CIs in order to gain understanding where risk mitigation measures should be applied. When assessing risk mitigation options, the benefits to each CI owner or operator should be considered along with the benefits to other CIs owners, (Utne, Hokstad, & Vatn, 2011). Therefore, there is need for an integrated risk management approach and governance aspects need to be addressed.

The methodology described is also having limitations. An important limitation is that it relies on prior risk assessments conducted on the CI level and on expert judgement. Therefore, subjectivity is introduced and the accuracy of the results depends on the quality of the information provided by stakeholders, (Theoharidou, Kotzinikolalou, & Gritzalis, 2011). Moreover, risk assessments regarding EWEs, especially when addressing climate change, are not very common even at the organisational level and stakeholders have limited experience with EWEs in the past. Subjectivity can be addressed by using fuzzy logic or the degree of reliability associated with each expert, (Setola, De Porcellinis, & Sforna, 2009) or by introducing additional measures such as the certainty of impact, (Kristensen, Aven, & Ford, 2006).Additionally, the study did not take into account the uncertainties related to future climate scenarios and the climate information used refers to the worst case climate scenario for the Netherlands.

Another limitation is that the methodology requires high level coordination among organisations. CI owners or operators usually are not aware of the complete picture of their CIs let alone of the system of CIs. Input from multiple people/disciplines within organisations as well as from end users is required to get the full picture. This causes data collection to be resource demanding, especially when the analysis involves many CIs. Moreover, in many cases stakeholders are not willing to share information due to confidentiality and privacy issues, liability issues and antitrust laws, (Rinaldi, Peerenboom & Kelly, 2001). Finally, the methodology presented in this paper does not address the risk at the society level; addressing the impact of EWEs at the municipality, national or even international level requires coordination among sector representatives, national and international authorities, (Theoharidou, Kotzinikolalou, & Gritzalis, 2011).

Future work should focus on assessing the uncertainties associated with risk assessment on the basis of future climate and socioeconomic scenarios and on addressing the subjectivity introduced in the methodology. Moreover, the study made an effort towards the assessment of cascading effects of common cause failures, however more research on the topic is needed and future work should focus on developing a more holistic approach.

Acknowledgements

We would like to thank the several organisations that participated in the case study for their cooperation and valuable input. The research project is part of INTACT project funded by the European Union Seventh Framework Programme (EU-FP7/2007-2013).

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