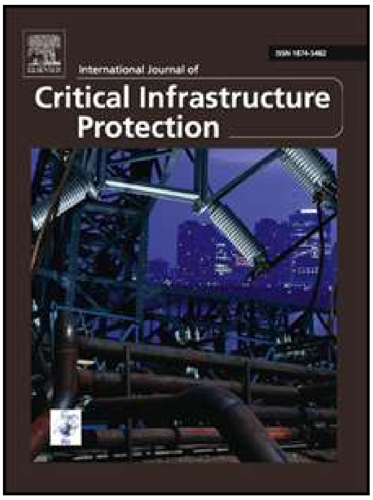

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Proposed methodology for Risk analysis of interdependent Critical Infrastructures to Extreme weather events

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Abstract

Growing scientific evidence suggests that risks due to failure of critical infrastructures (CIs) will increase worldwide, as the frequency and intensity of extreme weather events (EWEs) induced by climate change increases. Such 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. The methodology is developed and carried out for the Port of Rotterdam area in the Netherlands, which is used as a case study. The case study includes multiple CIs that belong to different sectors and can be affected at the same time by an initiating EWE. The proposed methodology supports the assessment of common cause failures that cascade across CIs and sectors. It is based on a simple, user-friendly approach that can be used by CIs owners and operators. The implementation of the methodology has shown that the severity of cascading effects is strongly influenced by the recovery time of the different CIs due to the initiating EWE and that cascading effects that result from a disruption in a single CI develop differently from cascading effects that result from common cause failures. For most CIs, vulnerabilities from EWEs on the CI level will be higher than the cascading risks of common cause failures on the system of CIs; moreover, cascading risks for a CI will increase after its recovery from the event.

Keywords: Critical Infrastructure, Extreme weather event, Climate change, Cascading Failure, Common cause failure

1 Introduction

Extreme weather events (EWEs) constitute a potential threat to human and natural systems, as they are expected to increase in terms of both of frequency and intensity, due to the warming of the climate system [22]. EWEs are among the most prominent global risks, lying in the higher-impact, higher-likelihood quadrant [57] 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) [54].

An extreme climatic event is usually defined as one that is rare within its statistical reference distribution at a particular place and time, normally as rare as or rarer than the 10th or 90th percentile of the observed Probability Density Function [43]. For events affecting infrastructures, the characterization of weather event as extreme is performed according to thresholds critical to the infrastructures [9]. CIs are defined as “those infrastructures whose services are so vital that their disruption would result in a serious, long-lasting impact on the economy and the society” [20]. Physical CIs include large scale, spatially distributed and complex networks such as energy supply, transportation, information and telecommunication, water and solid waste systems [17,57]. Those systems are vulnerable to extreme climate changes, since most of them have been designed under the assumption that climate is stationary [34]. Moreover, they are highly interconnected and heavily dependent upon each other and therefore a disruption in any of these systems can cascade across and affect the functioning of the entire system of CIs[44,7,22,17,57].

As climate becomes extreme it is likely that risks for CI failure will increase worldwide [8,17]. 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, monitoring and control [48].

However, the increasing complexity and interdependency of CI systems makes the severity of such risks very difficult to estimate. Moreover, CIs owners and operators tend to understand their own systems but usually are not aware of the resilience of the CIs that they are connected to [57]. Existing risk assessment methodologies that account for dependencies among CIs and address risks across different sectors are rather limited [24] and future climate scenarios are rarely considered [23]. Furthermore, they are complex and not user friendly [53].

To meet the above challenges of estimating the increasing complexity and interdependency of CIs, this paper proposes a methodology for analysis of risks of EWEs due to climate change to interdependent critical infrastructures. The methodology has been developed and carried out for the Port of Rotterdam area in the Netherlands. The methodology relies on stakeholders' experiences in estimating the impact of past EWEs on infrastructures and is intended to be used by CIs owners and operators. The work described in this paper is part of the EU-FP7 project with the acronym INTACT; the project addresses the resilience of CIs to EWEs and aims at bringing together innovative and cutting edge knowledge and experience to support stakeholders throughout Europe (and beyond) in their decision making to assess and mitigate risks of EWEs to their CIs [54]. In order to do so, case studies were selected across Europe that include different climate, landscape and environmental zones to provide coverage of a representative range of CI types and different levels of governance [55]. For this purpose the Port of Rotterdam area in the Netherlands was selected as one of the appropriate case studies, since it includes multiple CIs that belong to different sectors and are exposed to different types of extreme weather.

The rest of the paper consists of 4 sections. Section 2 contains the definitions of the different terms used in the study, as well as descriptions of existing risk assessment methodologies related to CIs. Section 3 describes the proposed risk analysis methodology adopted in this study, while Section 4 describes in detail the implementation of the methodology in the case study. Finally, Section 5 discusses the methodology and describes the main conclusions.

2 Literature review

2.1 Risk analysis

In the context of this study risk refers to the "result of a threat with adverse effects to a vulnerable system" [25]. Threat or hazard is defined as a source of harm or danger [33,32], while vulnerability refers to the predisposition of a society or a system to be negatively affected by single or compound hazard events. Birkmann et al. [6] argued that in the context of natural hazards, vulnerability should be described by key factors such as "the exposure of a society or system to a hazard or a 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 [6].

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 [32] According to Kaplan and Garrick [33], 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?"

To answer these questions one should identify relevant scenarios and estimate the probability of occurrence and the consequences of those scenarios. A 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" [52]. Probability can be interpreted either as a relative frequency or as a subjective measure of uncertainty about future events and outcomes [2]. 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 [13] and there are several well established methods to assess the magnitude and probability or return period of weather related to single-hazards [58,23]. However, the data usually used for hazard assessment are based on historical information rather than scenarios [23]. Moreover, there are several sources of uncertainty affecting future climate information, including natural climate variability, uncertainty regarding future emissions of greenhouse gases and modelling uncertainty [12].

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". The European Commission [14] defined the following impact criteria for CI assessments: (i) public effects (ii) economic effects (iii) environmental effects (iv) political effects and (v) psychological effects on the population, These criteria are evaluated in terms of scope (local, regional, national and international) and time (during and after the incident) [49](Most authors classify economic effects or costs of natural hazards into tangible and intangible and further into direct and indirect [38,40,28]. Intangible costs refer to damages to goods and services which are not easily measurable in monetary terms [39]. Direct costs are caused by impact due to 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 impacts that occur over time after a disaster or outside the place of disaster [39] and they can be particularly serious in case that a CI is affected by the hazard [21,29].

The level of risk can be estimated 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 [31]. 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 [3].

2.2 Existing risk assessment methodologies for CIs

Risk assessment methodologies for CIs can be broadly categorized in Sectoral methodologies that address the risks to the sector or even asset level and Systems approach that assess the CIs as an interconnected network [24]. The existing risk assessment methodologies for CIs that account for dependencies among infrastructures are rather limited [24]. One example that falls into the systems approach is that of Haimes [26], which applies risk assessment methodologies to System of Systems (SoS). A SoS approach was also developed by Theoharidou and Giannopoulos [51], to address risks from natural hazards on the asset, system and society level. Utne, Hokstad and Vatn [53] 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

Rinaldi, Peerenboom and Kelly [44] defined an infrastructure dependency as "unidirectional relationship between infrastructures, where the state of one infrastructure influences or correlates with the state of the other". Moreover, they 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 physical, cyber, logical and geographical. Infrastructure environment refers to the environment within which an infrastructure operates and involves economic, technical, legal, social, safety, business, security and public policy aspects, whilst 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 another 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 [44]. Nieuwenhuijs, Luiijf and Klaver [41] 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 depend all the states of operations [44]. Nieuwenhuijs, Luiijf and Klaver [41] empirically found that CIs have other sets of dependencies depending on their operational state.

The analysis and modelling of CI dependencies received increasing attention in the literature especially in the last few years and several approaches have been developed. Ouyang [42] broadly categorized modelling and simulation approaches for CIs dependencies into six types: Empirical, Agent based, System dynamics, Economic theory based, Network based and others, for example 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, and Gritzalis [50] and Kotzinikolalou, Theoharidou and Gritzalis [36] 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 assigned 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 [36].

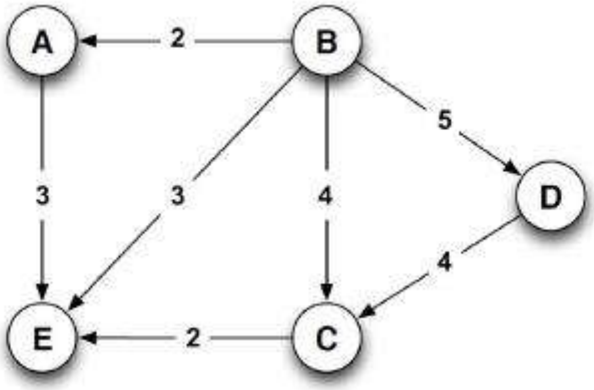

Fig. 1 - Example Dependency Risk graph between CIs [41, pg 101].

3 Proposed Methodology

This study uses 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 [41]. 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 [30] that follows the standards for risk process developed by the International Electrotechnical Commission, [31] 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 [10] (such as 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 [53, 51].

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 [53,27]. This can be done by performing a preliminary risk analysis to identify potential scenario 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 , subjective scaling, stakeholders elicitation or others [19].

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 the first approach is used, whereby existing risk and vulnerability assessments 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, it is assumed 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.), and its environment (economic growth, political stability) are dynamic in nature. Moreover, the study does 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 about future changes in weather extremes provided by climate and weather experts, as well as on hazards maps developed by Deltares, an independent institute for applied research in the field of water and subsurface in the Netherlands.

Impact assessment on the CI level

To assess the impact of EWEs on the CI level, firstly CIs vulnerabilities to EWEs in terms of exposure, susceptibility and resilience are identified and then the impact that results from those vulnerabilities are assessed against the following criteria:

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 human 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.

The above criteria were determined based on an existing risk assessment framework called RIMAROCC, [4] and after consultation with the stakeholders. They are also in line with the criteria provided by the European Commission for CI assessments [14]. 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 recent years, they are complex and not user friendly [53]. 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 to assess cascading effects**.** CIs are represented as nodes and dependencies as arrows that connect the nodes; on each arrow the type of the dependency (physical, cyber or logical) and a short description of the dependency are indicated. Following the approach developed by [50] and [36],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,. Cascading impact is assessed for 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 required using 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. This means that the methodology facilitates the use of existing information that is available within each organisation.

Combining common-cause and cascading failures

A widespread event can lead to common cause failures in multiple CIs that can in turn lead to multiple cascading failures at the same time. Although an event can have a very high impact, the combination of common cause and cascading failures has received limited attention in the literature. [36] 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 the fact that the initiating event may influence the state of operation of multiple CIs at the same time and that the dependencies between the CIs can be different depending on their operational state. The approach proposed in this paper considers how the initiating EWE will affect the state of operation of multiple CIs at the same time and examines how the recovery times of the different CIs influence the cascading effects. The approach and its application in a real case scenario are described in detail in Section 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 [11]. According to [18] “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 to demonstrate the validity and applicability of the INTACT approach at the broader (European) scale [55]. To understand the system of CIs within the port of Rotterdam and be able to analyse the risks and impacts due to EWEs on it, various data were required. The process used and the type of data collected are described in the following sections.

4.1 Data collection

In total 3 workshops and 25 interviews with representatives of 12 organisations were conducted in order to collect data from CIs owners, operators and risk managers regarding their experiences of impacts of EWEs on infrastructures and the decision-making processes related to them. The interviews were conducted in 3 phases; during the first two phases qualitative data regarding the CI systems, their vulnerabilities to EWEs, as well as the dependencies between them were collected. During the third and last phase CIs owners and operators subjectively ranked the impact of failures in other CIs due to EWEs 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.

4.2 System description

The Port of Rotterdam area is located at the Rhine–Meuse–Scheldt delta and it is the largest port in Europe. It forms a good case study, as seaports and their surrounding area are more likely to be exposed to EWEs due to their coastal location [11]. The total length of the port area is 42 km and it includes 12 500 ha (land and water, of which approximately 6 000 ha are business sites). The Port area is divided into smaller subareas or clusters that are commonly recognised as functional units, these are: Maasvlakte, Europoort, Botlek, Vondelingenplaat and Eemhaven/Waalhaven as shown in Fig. . The division in clusters is based on various criteria like topography, main type of activity, period of establishment and organizational aspects [16].

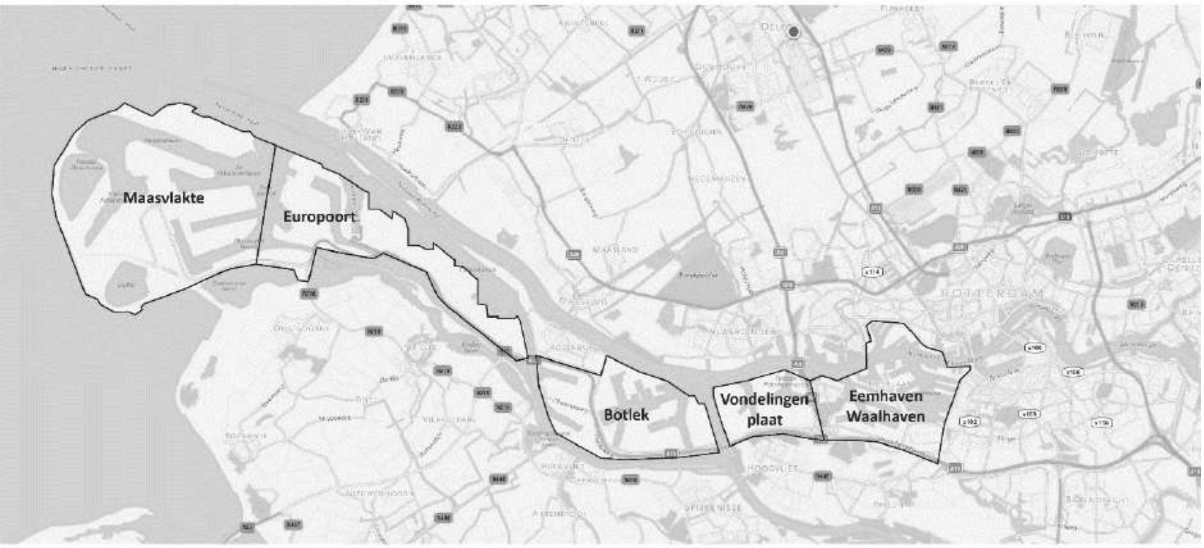

Fig. 2 - Map of the Port of Rotterdam area [1].

The port area includes multiple infrastructure networks that belong to a range of CI sectors, namely Energy, ICT/Telecommunications, Transport and Chemical. Table 1 shows an overview of the CIs and the main CI elements involved in the case study as well as of the relevant stakeholders' organisations and their roles [5].

Table 1 - CI and relevant stakeholders' organisations involved in the case study.

CI	Elements	Stakeholder Organisation	Role
Port Infrastructure	Nautical services & communication system, Cargo handling, storage and distribution system, Petro-Chemical and Energy Industry	The Port of Rotterdam Authority	Owner/landlord of the Port area. It manages, operates and develops the port and the industrial area of Rotterdam.
		Deltalinqs	Association that presents the interest of over 95% of of all logistic, ports and industrial enterprises in the mainport Rotterdam.
Electricity supply	High voltage network, mid voltage network, low voltage network	Tennet	Operates and manages the high voltage network in the Netherlands.
		Stedin	Operates and manages the mid and low voltage networks in the Port area.
Telecommunication	Fixed network, mobile GSM network (Global System of Mobile Communication)	KPN	Operates and manages the telecommunication networks and provides telecommunication services in the Port area.
		Vodafone	Operates and manages the telecommunication networks and provides telecommunication services in the Port area.
Roads	Main road A15	Part of Dutch ministry of Infrastructure and Environment	Operates and manages A15.
Railways	Betuwe Route	Prorail	Operates and manages Betuwe Route.
Inland Waterways	Nieuwe Waterweg, Calandkanaal, Beerkanaal, Hartelkanaal and Oude MaasBetuwe Route	Rijkswaterstaat	Operates and manages the inland waterways in the Netherlands.
Pipelines	The main pipeline corridor	The Port of Rotterdam Authority	Owns the ground and the civil works of the pipeline corridor within the Port area and is responsible for its exploitation and management.

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 [5]. 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 using CIrcle [15], an interactive touch table application, during a workshop; the results of the interviews were presented to the stakeholders and cascading effects caused by EWEs affecting the CIs of the Port of Rotterdam were identified. The hazards that are relevant to CIs were identified by ranking the list of EW types. The analysis showed that storm, followed by extreme heavy rainfall and snow, are perceived as the most critical weather types that are pertinent to 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 [5].

4.4 Risk analysis

The scenarios produced from the first phase of the study were reduced to a limited number, using interviews with stakeholders and existing risk and vulnerability assessments. The following scenarios were selected for detailed risk analysis: i) Inundation of Botlek area due to Coastal Flooding, ii) Extreme Wind speed and iii) Pluvial flooding due to Extreme Precipitation. This paper describes the detailed risk analysis for the inundation of Botlek due to coastal flooding with return periods of 1:1000 and 1:10000 per year as being the scenario with the highest impact on the Port of Rotterdam area. It also describes the results of the analysis for the extreme wind speed scenario.

4.4.1 Inundation of Botlek area due to Coastal Flooding

Coastal flooding constitutes a hazard for the Port of Rotterdam, as it is located outside the dikes and there is no legal protection framework for the area. Climate change and the induced sea level rise and excessive river discharge will increase the risk of coastal flooding and of fluvial flooding, respectively. According to the flow models used to estimate the probability of flooding and inundation levels for the Port area, based on current climate conditions and future climate scenarios [46,56], 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.

Botlek is an industrial area of great economic importance in the Port of Rotterdam area that was developed between 1940 and 1970. Based on the studies performed by [46,56] , 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 high spring tide. The studies have taken into account the effect of seiches and waves.

Climate change is taken into account by considering the KNMI (Koninklijk Nederlands Meteorologisch Instituut - Royal Netherlands Meteorological Institute) 14 climate scenarios for the Netherlands [35]. 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 provided a consistent picture of the changes in 12 climate variables, including temperature, precipitation and sea level, (Low or High). KNMI found no evidence for a possible change in the wind extremes; therefore it was assumed that wind extremes will not change. Wagenaar and de Jong and Slootjes and Wagenaar [46,56] calculated the inundation depth of Botlek for the reference year 2100 and the normative flood return periods of 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. The duration of the events will be limited to (24 to 36 hours) and the flow rate will be relatively low. The calculation showed that the inundation depths and the extent of the area that will be overflowed increases as the conditions become more extreme and that the water depth will be up to 2 meters at some locations. Based on the calculated inundation depths, the new return periods for the reference year 2100 were calculated as:

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

,where ‘decimeringshoogte’ denotes *the “Measure of the increase or decrease of the height of the tide with an increment factor of 10 as a result of the respective increase or decrease of the frequency* *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 [59]. 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 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

Impact assessment on the CI level

Like the rest of the Port of Rotterdam area, Botlek, includes many CIs that are vulnerable to flooding. The impact of coastal flooding on the CI level due to CI vulnerabilities is assessed against various criteria,using a Likert scale. The preliminary risk analysis based on the interviews and workshops showed that each impact criterion has a different relative importance, therefore different weights are assigned accordingly [11]. The total impact is calculated as the weighted average of the different criteria indicators. The criteria and the impact scales used for the impact assessment are shown in Table 3.

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

The impact scales used were based on the RIMAROCC risk assessment framework [30] and after consultation with the stakeholders. 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.

CIs in the Botlek are vulnerable to coastal flooding; the degree to which they are susceptible will depend on the water depth and the location of the assets. In most cases it was difficult for the CI owners to indicate the exact recovery duration of their CI from the event. Relevant information was collected for all the CIs by interviewing CI owners and operators as shown in Table 4.

Table 4 - CI vulnerabilities to coastal flooding of Botlek.

Affected CI	Vulnerable asset /operation	Exposure to hazard		Susceptible elements	Susceptibility factors	Time to recover
		1/1000 per year	1/10000 per year			
Roads	A15 in Botlek	A15 is flooded at multiple locations, in total around 2 km with 0.2 - 0.8 m water depth, locally higher	A15 is flooded at multiple locations, in total around 3 km with 0.2 - 2.0 m water depth, locally higher	Road embankments and foundation, electrical installations and systems like out stations, underpasses, vehicle traffic	Asset elevation, slope of embankments, local soil conditions, height of embankments	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.
Inland Waterways	Waterways in the Port area, vessel traffic	Waterways in the Port area	Waterways in the Port area	Vessel traffic	Open connection with the sea, area near to the coast	3 days
Port Infrastru-cture	Port infrastructure in Botlek	Around 35% of the area is flooded, water depth at the biggest part between 0.2 - 0.8 m	Around 45% of the area is flooded ,water depth at the biggest part between 0.8 - 2.0 m	Mainly distribution, petrochemical industry, intermodal transport, storage (breakbulk cargo)	Area elevation, assets elevation, type of asset	Some months to 1 year to get rid of the water and to repair damages to assets
Mid & Low voltage network	Mid & low voltage assets in Botlek	Around 35% of the area is flooded, water depth at the biggest part between 0.2 - 0.8 m	Around 45% of the area is flooded ,water depth at the biggest part between 0.8 - 2.0 m	Transform stations, Distribution stations, Street cabinets	Area elevation, assets elevation, type of asset	Weeks or even months
Railways	Betuwe route in Botlek	The rail track is flooded at multiple locations, in total around 2km with 0.2 - 0.8 m water depth, locally higher,	The rail track is flooded at multiple locations, in total around 3 km with 0.2 -2.0 m water depth, locally higher	Track, train detection systems, signals, switches, power buildings, installations, underpasses, rail traffic	Area elevation, assets elevation, type of assets	It depends on the extent of the damage. If Betuwe route is heavily damaged and entire sections of the track collapse, it may take 2-3 months. If only local damages, 2 weeks to 1 month.
Pipelines	Pipelines in Botlek	-	-	Pumps, valves, ICT control systems	-	3 days

Table 4 shows that the recovery time of A15 and Betuwe route is uncertain, hence 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 main road A15 and of the railways 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, i.e. 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 but it is conservatively estimated to take 2 months.

Figs. 3a and 3b show 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 represents 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 stop 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 that they exhibit limited dependency on Mid & Low voltage networks when they are under recovery. Unfortunately not enough data was available to collect and assess the impact of flooding on telecommunication networks.

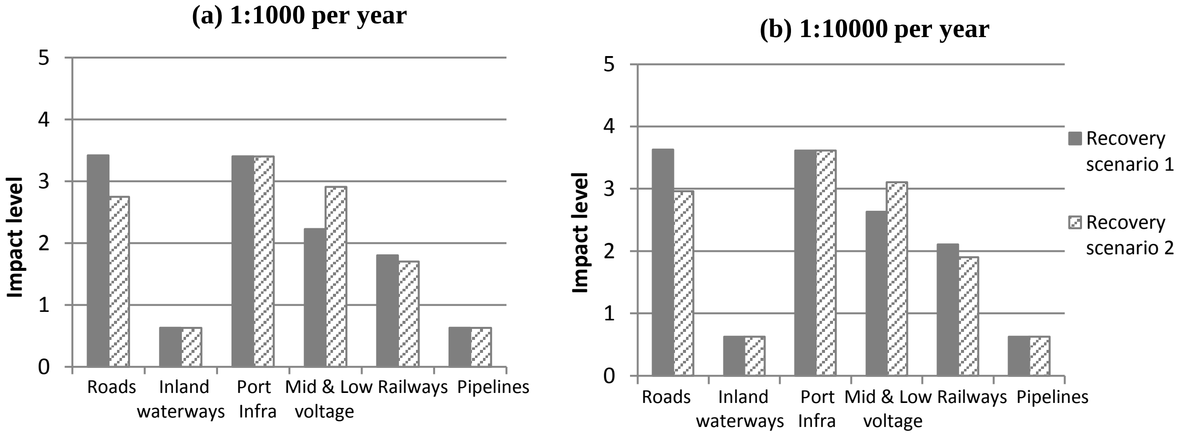

Fig. 3 - Impact on CIs due to vulnerability to coastal flooding with return period: (a) 1:1000 per year, (b) 1:10000 per year (current climate conditions).

Analysis of Dependencies and assessment of cascading effects

As described earlier, 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 sets of dependencies depending on their state of operation. Fig. 4 shows 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.

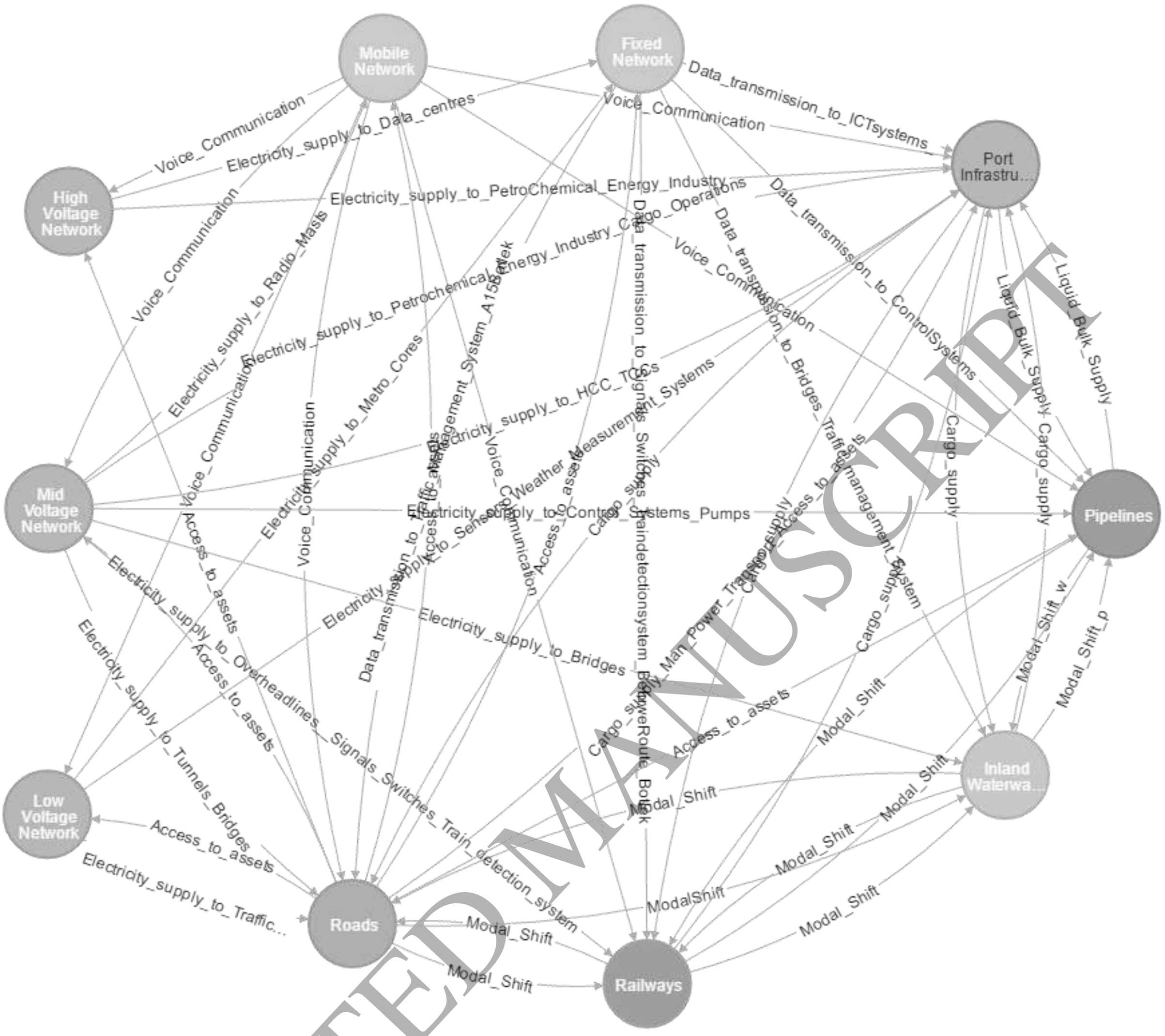

Fig. 4 - Dependencies between CIs of the Port of Rotterdam area under the normal state of operation.

In this work dependencies are quantified in terms of the risk or impact that a failure in one infrastructure will have on other dependent infrastructures. For simplicity it is assumed that the likelihood Li, j of a disruption being realized to CIj due to its dependency on CIi, is certain and hence equal to 1 which means that 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 similar weights as in the impact assessment due to vulnerabilities on the CI level to be able 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. Empirically it was found that the recovery time of the different CIs has an important influence on the cascading effects and that the level of the cascading impact depends on the duration of the disruption and does not usually evolve with time in the same way for all the dependencies [47]. Table 5 shows example of dependencies between the CIs in the Port area and the associated cascading effects induced by coastal flooding of Botlek based on return period of 1:1000 per year, for the 2nd recovery scenario whereby 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 the impact will start after the third day, when the Port area can be operated again. Based on the results shown in Table 5, a dependency graph can be constructed as shown in Fig. 5. The value associated with 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.

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 d	*1 w*	*1 m*	*2 m*
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 infrastru-cture	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

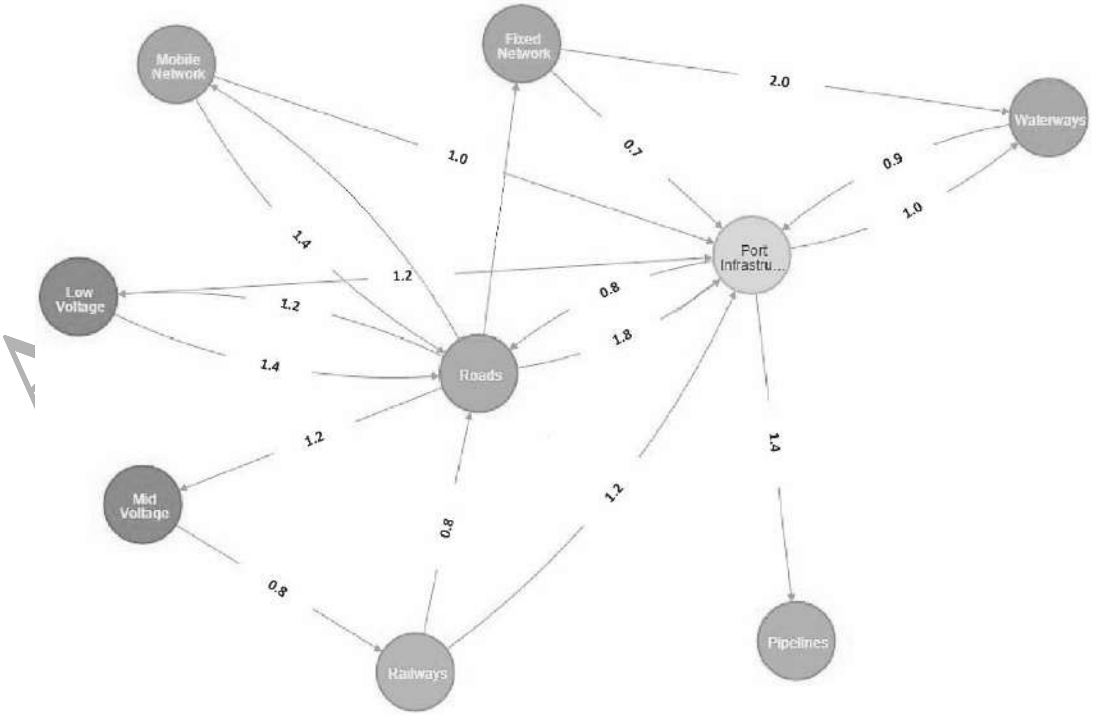

Fig. 5 - Dependency graph for Coastal flooding of Botlek with return period 1:1000 per year (current climate conditions) _ Recovery scenario 2.

Figs. 6 and 7 show relative scores of the total cascading impact level on each CI during a period of two months after the evacuation of the Port. Due to lack of sufficient data it is assumed that the impact growth rate is linear. In reality however the cascading impact does not evolve with time in the same way for all the dependencies between CIs. Figs. 6 and 7 show that the impact is modelled to start 3 days after evacuation, (i.e. when it is safe to return back to the Port area) assuming that the CIs operations will be shut down during that period. As some CIs receive cascading impact from more than one CI at the same time, it is assumed the total cascading impact on any CI from all its dependencies is equivalent to the highest impact caused by any one of these dependencies. 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 measure of the total impact level remains subjective.

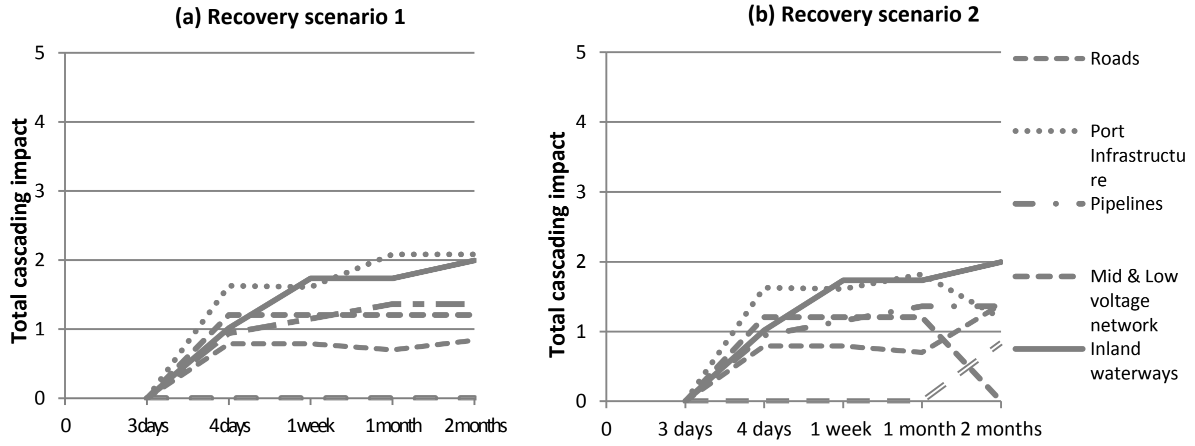

Fig . 6 - Total cascading impact per day received by each CI due to Coastal flooding of Botlek with return period 1:1000 per year (current climate conditions): (a) Recovery scenario 1, (b) Recovery scenario 2.

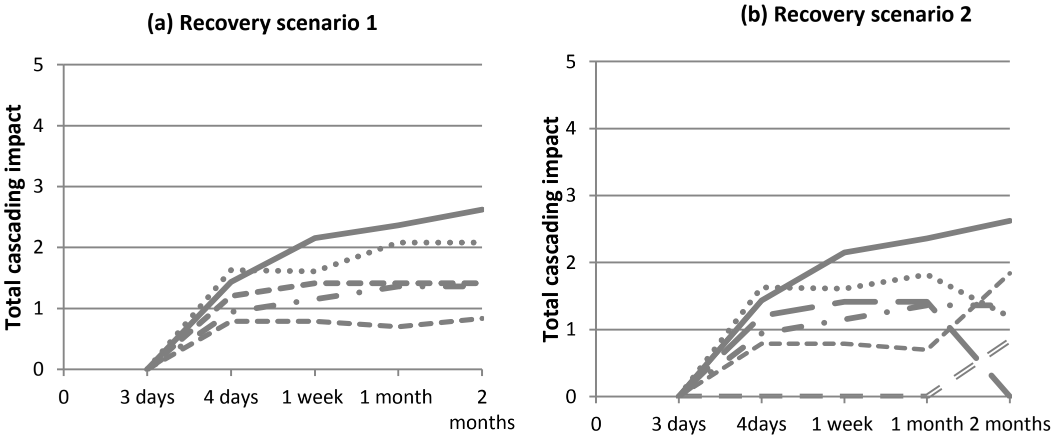

Fig. 7 - Total cascading impact per day received by each CI due to Coastal flooding of Botlek with return period 1:10000 per year (current climate conditions): (a) Recovery scenario 1, (b) Recovery scenario 2.

Figs. 6 and 7 show that Inland Waterways and Port Infrastructure have the highest cascading impact in most scenarios. Inland waterways are quite robust to flooding but they will be primarily affected during the period that the Port area is evacuated. Cascading impact is mainly related to reputation loss for operators and business costs for the users of Inland Waterways. The major part of the cascading impact on Port Infrastructure is related to reputation loss for the operators and business costs for the users of the system due to the unavailability of A15 and Betuwe Route. Outage of

Electricity supply and Telecommunications in Botlek have produced limited cascading impact on the Port Infrastructure, since most dependent Port operations will be under recovery. The limitation of cargo supply from Botlek will incur business costs for Roads, Railways and Pipelines users as well. The cascading impact for Roads and Railways transport providers and users is higher in the case of Recovery scenario 2, in which A15 and Betuwe route recover before the other CIs. Cascading impact to Railways starts after Betuwe Route recovers, since there is no alternative line for the Port area. Cascading impact to Roads increases after the recovery of A15, as Telecommunications services in Botlek will be limited and hence can delay the response of emergency services in case of an accident and consequently lead to safety loss.

It can be seen that the recovery times of CIs 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 depend on other CIs during recovery, due to the fact that electricity and most assets are remotely operated. Cascading impact on electricity increases with time until A15 recovers and diminishes after A15 becomes accessable to traffic again.

To summarise the results, the analysis has shown that 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 because most CIs will be directly affected by the EWEs and as a consequence they will be under recovery for a certain period of time. Based on the interviews with CIs owners and operators it was indicated that in most cases the cascading impact on a CI is higher when the infrastructure is not directly affected by the EWEs but its state of operation is influenced by its dependency on other CIs.

5 Discussion and conclusions

This paper describes a proposed methodology that uses a semi quantitative approach to analyse risks of interdependent CIs systems from EWEs, taking into account future climate scenarios. The methodology aims to assist CI owners and operators in assessing risk of EWEs and help them to mitigate the impact of the risks to their CIs. The methodology distinguishes between the risks that arise from vulnerabilities of the CI to EWEs and the risks caused due to the dependencies between CIs. It uses simple and user friendly graph based approach to analyse dependencies between CIs. The methodology has been demonstrated using the interdependent CIs of Port of Rotterdam area as a case study. The work described in this paper represents a contribution towards the assessment of cascading effects caused by common cause failures due to EWEs.

The work described in this paper has shown that for most CIs, risks to CIs vulnerabilities from EWEs on CI level will be higher than the cascading risks of common cause failures on the system of CIs. Moreover, the recovery time of the different CIs from EWEs strongly influences the cascading effects and for most CIs the cascading impact from other CIs system will increase after they recover from the initial EWE To certain extent most CIs owners and operators are aware of the risks of EWEs and climate change to their own systems; however, they are usually unaware of the resilience of the systems that they are connected to, as knowledge about vulnerabilities of CIs remains within the organizations themselves. This is why it is important that when assessing risk mitigation options, owners or operators of interdependent CIs system should consider the impacts to each CI along with the impacts to other CIs [53]. There is therefore a need for an integrated risk management approach and governance with regard to this issue.

The methodology described can be used by CIs owners and operators to provide them with broad estimates of the impacts of risks due to extreme weather events on their CIs, however it also has limitations. An important limitation is that it relies on prior risk assessments conducted on the CI level and on expert judgement which is subjective in nature. Hence the reliability of the results will be affected by the quality of the information provided by stakeholders [26]. Moreover, risk knowledge regarding EWEs, especially when addressing climate change, is not available even at the organisational level because stakeholders have limited experience with EWEs in the past. Some researchers suggested to address subjectivity using fuzzy logic or the degree of reliability associated with each expert [45] or by introducing additional measures [37].

Another limitation is that the methodology requires high level of coordination among the different stakeholders and organisations involved. CI owners or operators usually do not have complete pictures of their CIs let alone of the whole system of CIs. Input from multiple people/disciplines within organisations as well as end users is required to get a more comprehensive picture. This results in resource and time consuming data collection 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 [44]. Finally, the methodology does not address the risk to society or addressing the impact of EWEs at the municipality, national or even international levels. To do so will require coordination among sector representatives, national and international authorities [26].

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