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# Investigating the Importance of Critical Infrastructures' Interdependencies during Recovery; lessons from Hurricane Irma in Saint-Martin's Island.

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**Abstract.** Most research on critical infrastructure (CI) interdependencies focus primarily on their role in propagating system disruptions, neglecting their role during the restoration and recovery processes. The few studies incorporating interdependencies to model restoration, often consider hypothetical situations, cover a maximum of five CIs, or focus on short-term recovery. In an effort to bridge this gap, the presented study investigates the influence of CI interdependencies on the restoration of Saint Martin's CI network-of-networks after Hurricane Irma. Daily restoration data of 15 CIs was collected to build service restoration curves over a period of 28 months (medium- to long-term recovery). Obtained recovery curves revealed that while Irma took a proportionate toll on all Saint-Martin's CI, latter's recovery took a surprisingly long time. Our investigation found underlying interdependencies that were ignored in the plans, which could have led to a slower system restoration process. Accordingly, a holistic "network-of-networks"-based approach coupled with statistical modeling was followed to rank CI according to their criticality degree and correspondingly simulate a criticality-based systemic restoration plan. Key findings reveal that, in order to optimize CI recovery, the conventional silo-based and decentralized CI-by-CI restoration approaches should be complemented by a well-coordinated restoration strategy that recognizes and considers interdependencies.

**Keywords:** Urban risk, post-disaster recovery, networks, service restoration, graph theory.

## 1 Introduction

Despite considerable progress in Disaster Risk Reduction, the impact of severe events are often accentuated especially with Critical Infrastructure's (CI) failures. The latter considerably widen the spatial-temporal spectrum of damage and contribute to spreading risks [1]. CI are defined as the facilities/installations that provide societies with essential services [2] and can be summarized to electricity, transportation, telecommunications, drinking water and sewerage networks, and public institutions including schools, hospitals, post offices, etc. CI, also called lifeline systems, form the

backbone for the functioning of our modern societies by providing essential services to support the well-being of citizens [3]. The criticality of lifeline systems is highlighted especially in times of disasters and early recovery [4].

CI networks are not isolated but highly interdependent and interconnected [5] in a way that they form a complex network-of-networks also known as system-of-systems [6]. For instance, sometimes electricity needs water for cooling and requires telecommunication for SCADA (Supervisory Control and Data Acquisition), while water needs electricity to pump into distribution networks and telecommunication requires water for cooling and power for switches. These interdependencies are considered to be an asset in business-as-usual situations[7], offering beneficial outcomes (e.g., economic profitability, improved operational efficiency)[8][9]. Paradoxically, CI interdependencies may increase the system's fragility and lead to cascading effects [10]. Cascading effects, also known as cascading failures or domino-effects, are the failure of a CI causing the failure of dependent CIs and generating multiple downstream effects such as the fragmentation of the entire CI network-of-networks [11]. Most of the existing CI interdependency-related studies (e.g. [12]; [13];[14]) and operational guidelines mainly focus on the cascading failures to estimate damage, vulnerability or resilience of the network-of-networks in times of crisis.

However, CI interdependencies extend their effects to the recovery phase. Restoration curves can be used to quantify infrastructures' interdependencies [15–17]. Some interdependencies, not existing in business-as-usual situations or not obvious under normal conditions, may be revealed in times of recovery [18]. This type of interdependencies make the services more difficult to restore [19]. Restoring the CI networks' services as quickly as possible and in an optimal way is the main objective of CI operators and managers. Particularly that the latter are often faced with a tremendous pressure placed by the affected population, the media, the political and administrative leadership to resume the vital provision of basic services as quickly as possible [20]. Adopting a silo approach that doesn't recognize the fundamental role of CI interdependencies in the recovery of the network-of-networks [21,22], can make the most meticulously established CI recovery plans result in chaotic domino effects. The latter would hamper the recovery of the entire society. According to Kanno et al. [23], it is thus vital to consider CI interdependencies for a better understanding of the complex restoration process and their potential for a timely-efficient and successful recovery. A successful recovery is heavily dependent on a centralized/joint restoration strategy of disrupted services [3].

Martell et al. [24] pointed out that although interdependence is increasingly recognized as an important factor, restoration models incorporating it are still limited in number. The majority of the existing analyses, methods, and modeling of interdependent restorations consider hypothetical situations [25], and only few explore the recovery of CI in an actual post-disaster scenario using real-world data (e.g.,[26], [27]). Furthermore, a maximum of five CIs in the network-of-networks (e.g., [28]) were tackled and over a restoration period of maximum seven months (short-term recovery, e.g., [29]).

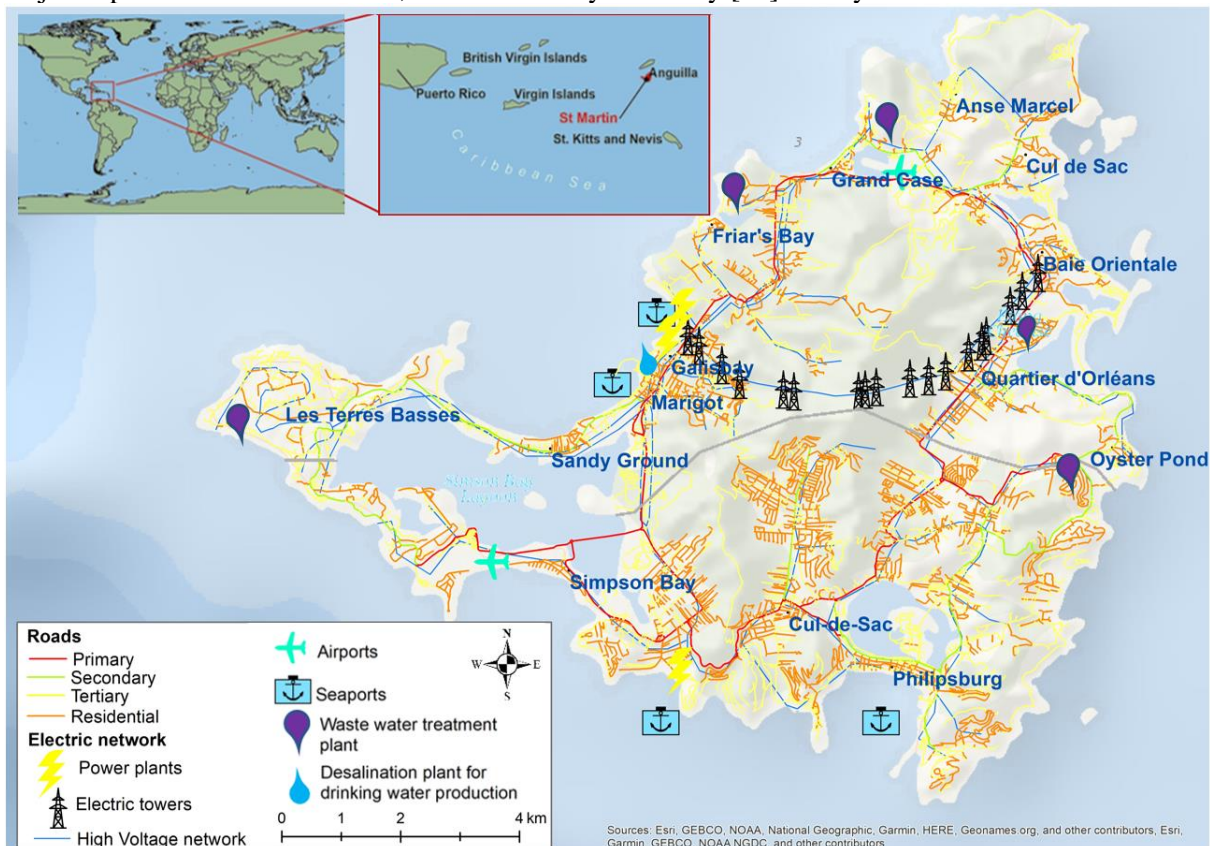
In response to all the above discussed issues, this study provides a better understanding of the role of the CIs' interdependencies during recovery and how they can be used to plan for an optimal restoration strategy. The current study focuses on real-world data from Saint-Martin's island after the occurrence of hurricane Irma. The compiled data covered the daily restoration rates of 15 CIs and over a period of 28 months (medium- to long-term recovery). Disruption and resumption of the CI's services on the island are meticulously studied to uncover underlying interdependencies and the adopted restoration strategy. The outcomes of this analysis are used afterwards to propose a centralized strategic post-disaster restoration planning by using graph theory and statistical modeling. The proposed restoration strategy is validated through concertation with local CI operators.

The remaining sections of this paper are organized as follows: Section 2 introduces the case study, section 3 presents the adopted methodology, section 4 illustrates and discusses the obtained results and section 5 concludes this paper by revealing the main contributions of this work and proposing some research perspectives.

## 2 Case study

### 2.1. Study area

Saint-Martin's island is a French overseas territory located in the northeast of the Caribbean Sea (Figure 1). Despite its small area of only 87 km<sup>2</sup> the island is divided, since 1648, into two political entities: on the North, Saint-Martin (53 km<sup>2</sup>), belonging to France and having Marigot as its capital; from the South side, Sint-Maarten (34 km<sup>2</sup>), belonging to Netherlands and having Phillipsburg as its capital. In terms of socio-demographic characteristics, since the early 1980s, the French side of island witnessed a considerable population growth [30]: from only 8,072 inhabitants in 1982 to more than 35,700 in 2017 as estimated by INSEE (French National Institute of Statistics and Economic Studies). The topography of the island characterized by steep hills in central inlands has created demographic pressure especially in the coastal areas of Saint-Martin. Consequently, the greatest concentration of CI is observed in the lower coastal areas (Figure 1). Grand-Case Esperance airport in the French side, Princess Juliana International airport in the Dutch side, roads, drinking water production plant, waste water treatment plants, power plant, Galisbay and Marigot seaports in the French side and Phillipsburg seaports are all highly exposed to cyclonic hazard. Saint-Martin's CI network-of-networks is characterized by accentuated interdependencies due to the insular case. Public services and CI are of major importance in Saint-Martin, whose economy is tertiary [31] mainly oriented towards tourism.



**Figure 1.** Saint-Martin's location and main CI networks.

The urbanization in low coastal lands, without appropriate preventive measures (e.g., hurricane-proof buildings[32]), is problematic especially that Saint-Martin is located within the Caribbean hurricane belt [33]. The island witnesses the occurrence of hurricanes particularly from September until mid-October. Saint-Martin witnessed numerous intense hurricanes since 1950: Hurricane Dog in 1950 (Category 3), September 1<sup>st</sup>, 200 km/h; hurricane Donna in 1960 (Category 3), September 5<sup>th</sup>, 204 km/h, 7 killed, very heavy damage on the island; hurricane Luis in 1995 (Category 4), September 5<sup>th</sup>, 213 km/h, leaving 1,000 homeless and 9 killed; Lenny in 1999 (Category 4), November 19<sup>th</sup>, 213 km/h, 13 killed. The majority of these hurricanes have caused destructive disruptions to the island's living conditions, infrastructure, and economic activity. Wind, heavy rain, landslides, and/or marine submersion

triggered by hurricanes can heavily impact buildings and infrastructure (e.g., cause total destruction) [34]. Damage varies with hurricanes' intensity [35]. Hurricanes' intensities are categorized from 1 to 5 according to the Saffir-Simpson scale which is proportional to the wind speed: Category 1 (119-153 km/h) can cause some damage, Category 2 (154-177 km/h) can cause extensive damage, Category 3 (178-208 km/h) can cause devastating damage, Categories 4 and 5 (209-251 km/h and 252 km/h or higher) can both cause catastrophic damage [36]. The damage to CIs can cause destructive disruptions to the islands' living conditions and economic activities often mainly oriented towards tourism. The insular character and the small surface of islands like Saint-Martin, along with the underlying CI interdependencies, multiply and amplify hurricanes' impacts to a systemic risk with a national scale.

## 2.2. Hurricane Irma

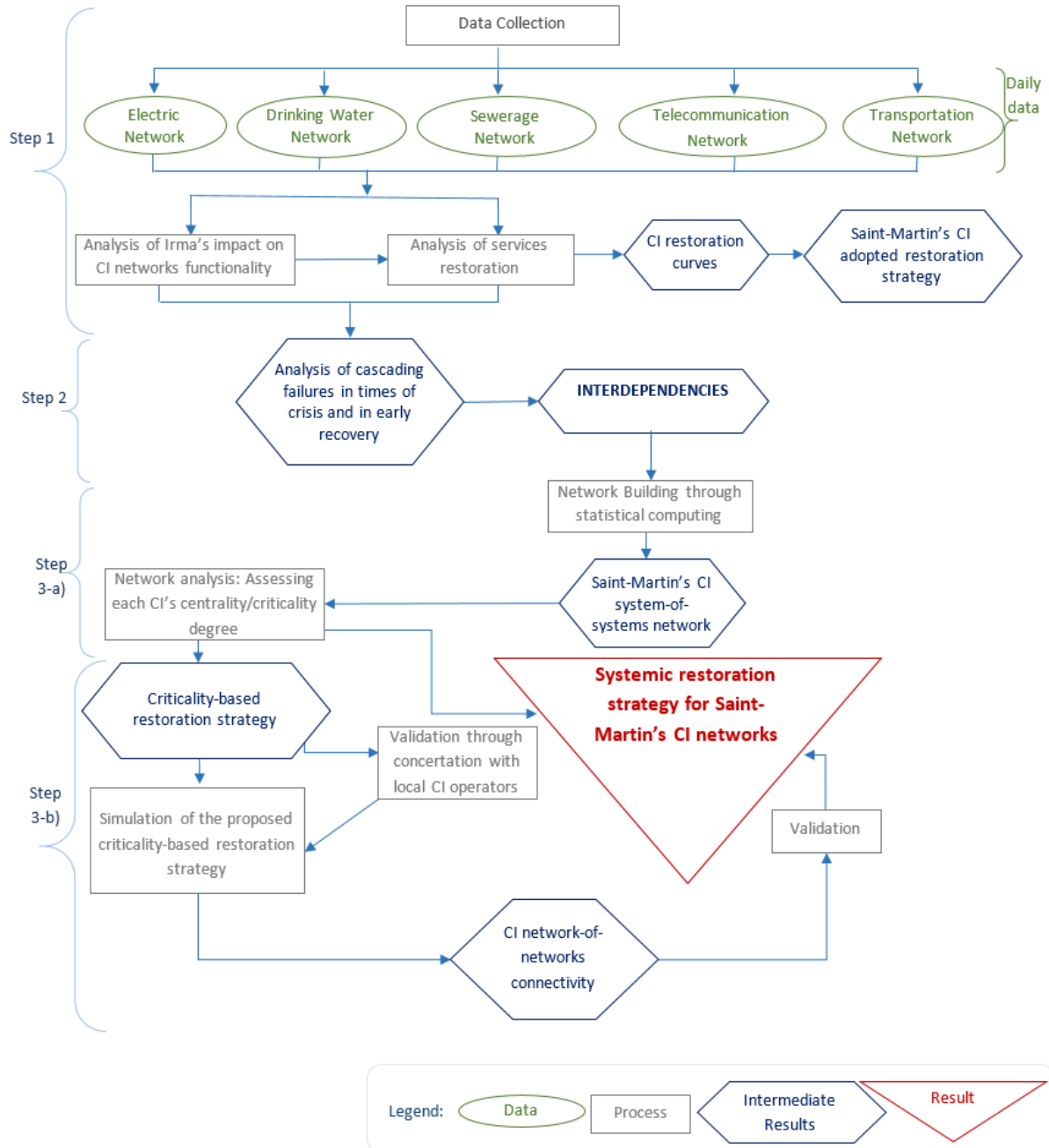
Irma is a Category 5 hurricane on the Saffir-Simpson scale and has been recorded as one of the most severe Atlantic hurricanes [37,38] offering a real worst-case scenario. Irma formed from a tropical wave near the Cape Verde Islands, rapidly attained a category 1 hurricane on August 31<sup>st</sup>, and crossed the Atlantic Ocean before weakening significantly on its way to Georgia by September 11 (figure 2). In the eye of the hurricane [39], Saint-Martin was severely hit by Irma at the dawn of September 6, 2017 [40]. According to Rey et al. [41], maximum wind speeds reached 320 km/h and waves of heights of 10 m were observed on the island. Pillet et al. [42]'s observations suggest that wave heights could have possibly exceeded 10m. The toll of this hurricane turned out to be particularly heavy; 11 deaths and around 1.2 billion euros of economic damage were recorded in Saint-Martin alone [43,44]. After the occurrence of Irma, Saint-Martin was disconnected from the world, isolated, without electricity, water or any means of communication for days. The majority of the CI were considerably damaged due to the combined action of high winds, heavy precipitations and flooding from high sea levels and waves [45]. CI service resumption was relatively slow and the recovery took more time than expected causing destructive disruptions to the islands' living conditions and economic activities often mainly oriented towards tourism. Consequently, reducing the time of recovery from recurrent hurricanes in Saint-Martin is of major importance to increase its resilience.



Figure 2. Hurricane Irma's path in the North Atlantic, a focus on Saint-Martin Island.

### 3 Material and methods

The proposed methodology, summarized in figure 3, consists first of examining the service disruption and restoration patterns of Saint-Martin's CI following Irma. This analysis is meant to uncover interdependencies and reveal their significance during recovery. As a final output, the adopted methodology will inform an enhanced restoration plan for the CI network-of-networks.



**Figure 3.** Flowchart of adopted methodology, applied to Saint-Martin's CI in the aftermath of hurricane Irma.

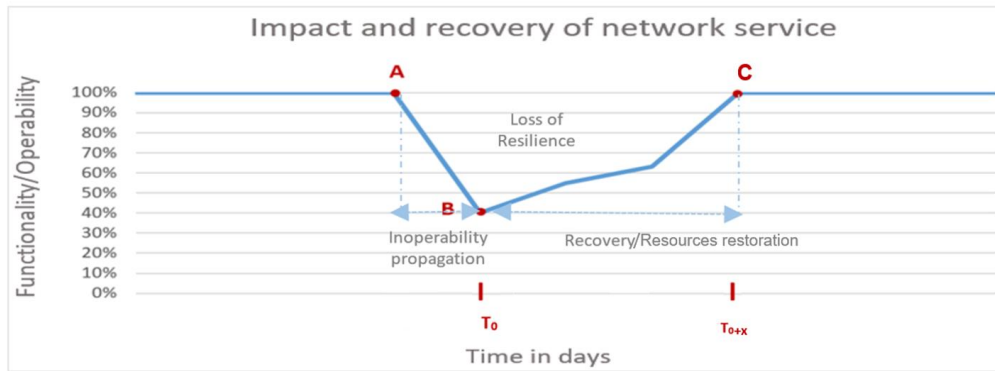
To analyze the CI network-of-networks, all Saint-Martin's CI networks were tackled: electricity, potable and sewage water, telecommunications (mobile, landline and internet), and transportation (roads, airports and seaports). Multiple sources were used to conduct a thorough inventory necessary for the adopted methodology: qualitative and quantitative data were collected from reports, studies, press releases, news feeds, or newsletters from the websites of local authorities and network operators in Saint-Martin and through crowdsourcing/social media (Facebook and Twitter). This analysis was

supplemented by open-ended interviews that took place on the island (September 2021) and in Paris during the “Retex Irma” conference organized by the French High Committee for Civil Defense (HCFDC), on the 13th of September 2018, at the French Insurance Federation (Paris). A considerable part of the collected data was from the daily situation reports of the French Directorate General of Civil Security and Crisis Management (Direction Générale de la Sécurité Civile et de la Gestion des Crises—DGSCGC) and the French Interministerial Crisis Management Operational Center (Centre Opérationnel de Gestion Interministérielle des Crises-COGIC). These reports offered detailed information about the impact of Irma on CI networks and the daily progress of recovery.

Three main steps were followed in the adopted analysis: Step 1) Analysing Irma’s impact on CI services and subsequent restoration, Step 2) Analysing cascading failures and interdependencies between CI networks, and Step 3) Building the CI network-of-networks and conducting network analysis to develop an optimal restoration strategy.

Step 1) “Analysing Irma’s impact on CI services and the subsequent restoration/resumption” consists of assessing and tracking CI recovery on a daily basis over 28 months.

Restoration curves will be established to present the degradation of the service and its progressive return to normal functioning state as a function of time (Figure 4). The damaging cyclonic impact (winds, flooding, etc.), tangible or intangible (caused by interdependencies), is observed by the reduction in performance from point A (at time  $T_0$ ) to point B. The restoration process starts at point B to the full recovery at point C (at time  $T_{0+x}$ ). Restoration curves can reveal the resourcefulness explained by the technical and organizational dimensions behind the adopted restoration.



**Figure 4.** Time-dependent service disruption/restoration metric of the studied CI network

The above temporal dynamic analysis is meant to reveal the adopted restoration strategy  $R_{adopted}$  (equation 1). The latter can be written as a sequence of CI restored at time step  $t_{0+x}$  with  $1 \leq x \leq N$  the total number of CI:

$$R_{adopted} = \{n^{t_0+1}, n^{t_0+2}, \dots, n^{t_0+x}\}$$

Equation 1. CI restoration strategy.

Step 2) consists of analysing the cascading failures during Irma’s occurrence and in the early recovery phase in order to reveal CI interdependencies. Interdependencies are often investigated in pre-disaster phases to reveal possible cascading failures through complex predictive modeling, “What If” simulations and projection of multiple scenarios. In these studies, the role of interdependencies in times of services restoration is often underestimated or even neglected. In the current study, a real worst-case scenario is offered by the occurrence of Irma (one of the most intense hurricanes ever recorded in the Atlantic Ocean). On-site observations and validated facts allowed the investigation of cascading failures consequently uncovering existing interdependencies and their roles both at the time of response and at the time of recovery. Cascading failures have thus been triggered from either 1) interdependent service disruption and/or 2) interdependent recovery/service restoration. These types of

interdependencies were considered: physical (operation on one depends on output of other) [5], [27], functional (operation of one infrastructure system is necessary for the operation of another infrastructure system) [47], cyber/informational (states depends on information transmission) [5], logical (states depends via control mechanism), input (system requires input from another system) and/or mutual (at least one infrastructure operation relies on others) [48]. An interdependency matrix (matrix  $a_{ij}$  with value in row  $i$  and column  $j$  indicates arc  $(\overrightarrow{i,j})$ ) will be established from the collected and analysed information. This matrix shows the degree of interdependence (high, moderate, low or null) between networks. A high degree (attributed value=3) shows a direct interdependence (without autonomy and total disruption) which is revealed in times of crisis and also in times of recovery. A moderate degree (attributed value=2) shows the presence of a direct interdependence causing service disruption (low/partial autonomy and operation in degraded mode and possible disruption after a few days). A low degree (attributed value=1) indicates that there is an indirect interdependence revealed especially in recovery times (autonomous operation and without degraded mode but necessary during recovery). And a null degree (attributed value=0) of interdependence indicates that two networks are completely independent.

CI restoration planning involves a complicated scheduling problem related to CI interdependencies that is difficult to solve analytically. Therefore, Sub step 3-a) follows a network-based approach for building the CI network-of-networks. The established interdependency matrix (matrix  $a_{ij}$  with value in row  $i$  and column  $j$  indicates arc  $(\overrightarrow{i,j})$ ) in step 2 will allow the creation of the CI network-of-networks to a core model based on geometric networks [49]. Saint-Martin's CI network-of-networks is assimilated to a graph  $G(E, V)$  representing a set of  $|V|$  vertices/nodes  $n_{ij}$  which are herein the CI interconnected by  $|E|$  directional junctions/edges/arcs  $(\overrightarrow{i,j})$  represented by the previously uncovered interdependencies between CI. Attribute values that represent interdependency level, according to values of the interdependency matrix obtained in step 2), were considered and assigned to each edge as weights  $w_{ij}$ . Network analysis following statistical modeling, according to *modern graph theory* concepts, is then conducted to analyse each CI/node characteristics in the network-of-networks. In graph theoretic terms, the degree centrality of a node  $i$  is defined as the number of its ties/connections. Nodes with high centrality are considered to be the most critical and the most important in the network[50,51] due to their influence on the continuity of operation (flow robustness [52]) in the rest of the network. The continuity of operation is provided by the network's connectivity. In addition to the number of ties, their weights and direction should be considered for restoration planning. According to [53], the strength  $s_i$  (or weighted vertex degree) of a node  $i$  is a natural measure of its importance or criticality in the network (equation 2). Equation 3 shows a standardized measure of  $s_i$ .

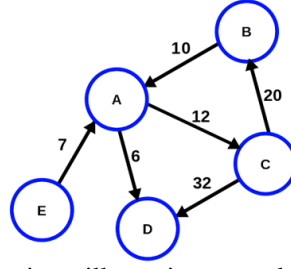
$$s_i = \sum_{j=1}^N a_{ij}w_{ij} \quad (i \neq j)$$

Equation 2. Node strength [53] with N the total number of nodes.

$$s'_i = \sum_{j=1}^N a_{ij}w_{ij} \times \frac{\sum(\overrightarrow{i,j})}{\sum s_i} \quad (i \neq j)$$

Equation 3. Standardized node strength

The importance/criticality of nodes in relation to their out-strength resides in the crucial role they play not only in maintaining the network's connectivity but also in accelerating its restoration after disconnection. The out-strength of a node, as the total weight of its outgoing connections, is explained in a simplified way in figure 5.



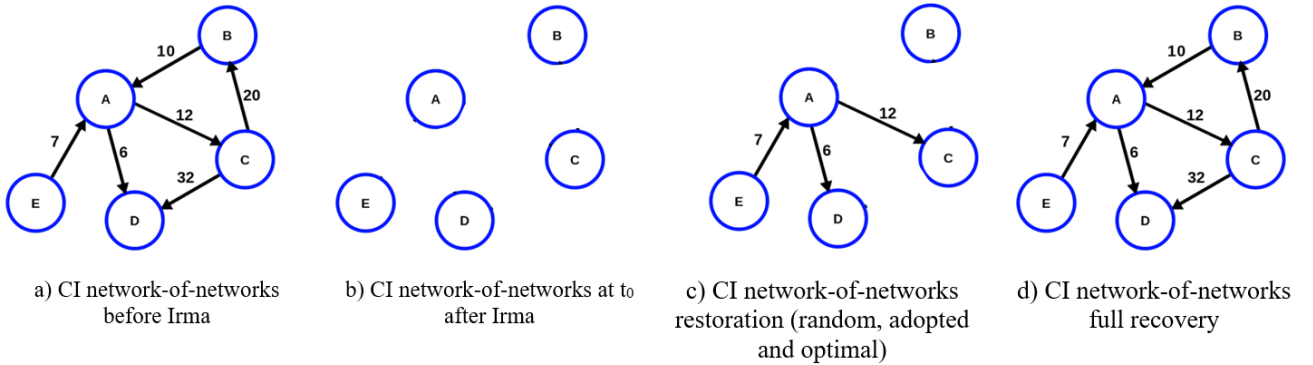
**Figure 5.** Characterizing critical nodes in an illustrative example for a simple network; node C has the highest score of out-strength, followed by nodes A, B and E, respectively. Node D has an out-strength score equal to 0.

In sub-step b), a criticality-based restoration strategy is set. The statistical modeling of network analysis in sub-step 3-a) will allow to set a criticality-based restoration strategy according to the uncovered characteristics of CI. The criticality-based restoration strategy  $R_{optimal}$  (equation 4) can be written as a sequence of CI restored  $n$  at time step  $t_{0+x}$  with  $1 \leq x \leq N$  the total number of nodes, and the nodes strength  $s_1 > s_2 > \dots > s_x$ : CI are restored in descending order of their out-strength centrality.

$$R_{optimal} = \{n_{s_1}^{t_0+1}, n_{s_2}^{t_0+2}, \dots, n_{s_x}^{t_0+x}\}$$

Equation 4. Criticality-based CI restoration strategy.

A statistical model is run to assess the network's connectivity. CI network-of-networks's connectivity denotes in this study the maximum serviceable level (electricity, drinking water, sewerage, telecommunications and transportation) that can be maintained when one or more CIs are non-operational. CI (nodes) were first removed from the network-of-networks and regarded as disconnected nodes (like in  $t_0$  after Irma) to be restored (figure 6).



**Figure 6.** Adopted simulation in an illustrative example for a simple network.

A worst-case scenario like Irma is considered, where all CI networks are damaged and need to be restored. CI were then added back into the network one by one and following: 1) a random restoration (random sequence of restored nodes), 2)  $R_{adopted}$  (equation 1) considered as the reference strategy adopted after Irma and 3)  $R_{optimal}$  (equation 4) considered as the targeted restoration in which CI are restored in descending order of their out-strength centrality. The CI network-of-networks functionality/connectivity  $C_{t_0+x}$  (equation 5) was evaluated after each computation of nodes integration to the network at time step  $t_0+x$ , and with  $1 \leq \alpha \leq N-1$ .  $C_{t_0+x}$  reveals the percentage of "connectivity gain" which corresponds to the ratio between the number of relationships made possible after a CI is restored and the total number of possible relationships when the network is not disturbed.

$$C_{t_0+x} = \frac{s'_{n_{s_x}^{t_0+x}} + s'_{n_{s_{x-1}}^{t_0+x-1}} + s'_{n_{s_{x-2}}^{t_0+x-2}} + \dots + s'_{n_{s_{x-\alpha}}^{t_0+x-\alpha}}}{\sum(\bar{l}, \bar{j})}$$

Equation 5. Connectivity of CI network-of-networks.

To validate the proposed criticality-based restoration strategy, concertation with local CI operators took place.

This analysis will reveal the role of interdependencies during recovery and the importance of a strategic systemic restoration for an efficient recovery of the entire CI network-of-networks. Simulating systemic restoration is capable of capturing the changing dynamics of the overall network-of-networks' behaviour, with the underlying characteristics and the interrelated interactions (interdependence and connectivity) throughout recovery.

## 4 Results and discussion

Obtained results are presented and discussed in three sections. Section 1 reveals the disruption and restoration of Saint-Martin's CIs after Irma, section 2 tackles the cascading failures and uncovers the underlying interdependencies and section 3 highlights the main finding of this study that is the optimal systemic restoration plan for the CI network-of-networks of Saint-Martin.

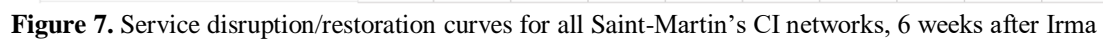
### 4.1 CI's services disruption & restoration

Analysis of collected data uncovered the services disruption and the dynamics of CI's restoration after Irma (reference restoration scenario  $R_{adopted}$ , equation 6). It is important to note that, according to available resources, the adopted restoration strategy overlooked CI interdependencies and followed a silo-based approach.

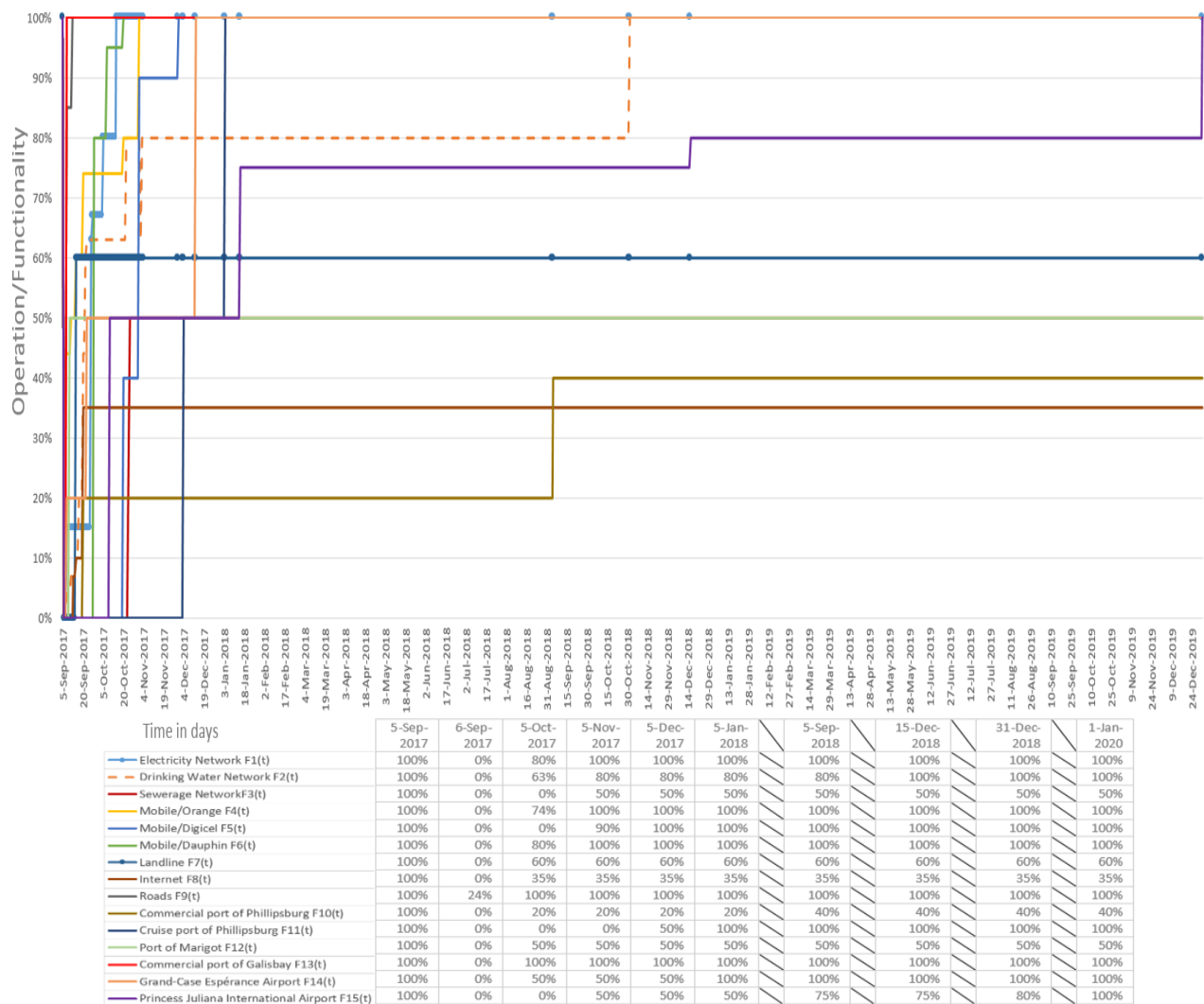
$$R_{adopted} = \{Port^{t_0+1}, Roads^{t_0+2}, Electricity^{t_0+3}, Mobile^{t_0+4}, Airport^{t_0+5}, \\ Drinking\ water^{t_0+6}, Landline^{t_0+7}, Internet^{t_0+8}, Sewerage^{t_0+9}\}$$

Equation 6. CI restoration strategy adopted in Saint-Martin after Irma.

CI disruption/restoration curves were established (Figure 7 and figure 8 covering respectively 6 months and 28 months after Irma) to provide a general understanding of the degradation of services and the progressive return to normal functioning state as a function of time. These curves shed the light on the fact that no CI network in Saint-Martin has resisted to Irma. There was a disruption of all services on September 6, 2017. No CI was functioning except for the road network which could only keep 24% of its functionality. While hurricane Irma took a proportionate toll on all CI networks of Saint-Martin, the analysis revealed that services restoration seemed completely disproportionate. In fact, recovery times obtained varied from 0.3 weeks (for Galisbay port) to more than 108 weeks (and still not reached for some networks at the time of the study). CIs which recovery took a relatively long time (whose dimension of recovery speed is the least) may be caused by technical and/or organizational failures or considerable interdependencies that blocked their rapid return to operation.



**Figure 7.** Service disruption/restoration curves for all Saint-Martin's CI networks, 6 weeks after Irma



**Figure 8.** Service disruption/restoration curves for all Saint-Martin's CI networks, 28 months after Irma

## 4.2 Cascading failures and underlying interdependencies

The analysis of the prompt disruption and progressive restoration of services, observed in the obtained curves, unveiled the cascading failures of Saint-Martin's CIs. In contrast with conventional pre-event analyses, this analysis offered the possibility to include first and second degree interdependencies (i.e. interdependence in Business-as-usual (BAU) time and during recovery time respectively) as defined by [37]. The inoperability of a CI can be related to that of another one, in response phase and during recovery phase. In fact, the non-linear nature of the service recovery curves of a considerable number of the studied CI above may be linked to the lack of resourcefulness. Resourcefulness is *“the availability of various types of human, financial, and infrastructural resources during planning, absorption, and recovery stages”* [55]. These resources are often provided by other CIs implying interdependencies (physical, functional, cyber, logical, input and/or mutual explained in table 1 below). It is important to study and understand these interdependencies, and to recognize their roles in order to moderate their effects during the recovery phase through an optimal restoration strategy.

**Table 1.** Observed CI's cascading failures and uncovered interdependencies following Irma in Saint-Martin.

	<b>BAU Interdependencies</b>	<b>Interdependencies in times of recovery</b>
<b>Electric network</b>	-No outages due to damage to another network	-The restart of production units have been delayed due to interdependence with the water network (demineralized water supply) needed to cool the generators -The restart could also have been slowed down if the oil stock had been damaged; the electrical network of Saint-Martin shows a strong dependence on fuel oil and, ultimately, on its means of transport (roads and seaports). -The resumption of electricity also revealed an interdependence with the transportation networks (repair crews, experts and equipment brought from abroad, etc.)
<b>Drinking water network</b>	-Outage due to electricity blackout implying a direct and total dependence of the drinking water network on the electricity network	-The resumption of drinking water wasn't possible without electricity supply -The resumption of drinking water also revealed an interdependence with the road network; teams' access to water network repair works was delayed due to the rehabilitation of the traffic lanes.
<b>Sewerage network</b>	-The sewerage network in Saint Martin have had direct failures due to the disruption of the electricity network (WWTP totally stopped).	-A strong dependence on the road network, especially on the main road (insular character), was also revealed in times of recovery; teams found it difficult to be able to go to their place of work (blocking and saturation of the roads) and thus the tasks of restarting the functioning of the wastewater system (work operations, clearing, restarting...) was complicated and delayed.
<b>Mobile network</b>	-No outages due to damage to another network	-Mobile networks are also dependent on transport networks for the supply of equipment and emergency response teams.
<b>Landline network</b>	-Landline communications have been completely cut off on the island due to major damage to the power plant, revealed that the landline network is directly dependent on the electricity network.	-Even when connectivity was restored, access to the landline network was impossible due to the still largely faulty electrical supply. Telecommunication boxes are directly supplied with energy by the subscriber's electrical network via metal segments. -Landline network is also dependent on transport networks for the supply of equipment and emergency response teams.
<b>Internet network</b>	-Internet connection has been completely cut off on the island due to major damage to the power plant and the landline network, revealed that the telecommunications network is directly dependent on the electricity network and on the landline network.	-Even when connectivity was restored, access to the internet network was impossible due to the still largely faulty electrical supply. Telecommunication boxes are directly supplied with energy by the subscriber's electrical network via metal segments. -The internet connection depends directly on the landline network. -Internet network is also dependent on transport networks for the supply of equipment and emergency response teams.
<b>Road network</b>	-The road network shows a partial dependence on the electricity network for lighting and road traffic signs.	-Although roads were unblocked days after Irma, they were still partially nonfunctional because of the electricity outage necessary for lighting and road traffic signs.
<b>Airports</b>	-Dependence on the electricity network, drinking network, sewerage network, internet and landline networks and on the road network.	-The airports' services resumption was delayed by the outages of the electricity network, drinking network, sewerage network, internet and landline networks and the road network.
<b>Seaports</b>	-Dependence on the electrical network and the road network for operation.	-The ports' services restoration was delayed by the outage of the electrical network and the road network's inoperability.

The revealed interdependencies, in table 1 above, allowed the development of the interdependence matrix of Saint-Martin's CIs (Figure 9). This matrix shows the degree of interdependence (high, moderate, low, or null) between networks. A high degree (attributed value=3) shows a direct interdependence (without autonomy and total disruption) which is revealed in times of crisis and also in times of recovery. A moderate degree (attributed value=2) shows the presence of a direct interdependence causing service disruption (low/partial autonomy and operation in degraded mode and possible disruption after a few days). A low degree (attributed value=1) indicates that there is an indirect interdependence revealed especially in recovery times (autonomous operation and without degraded mode but necessary during recovery). And a null degree (attributed value=0) of interdependence indicates that two networks are completely independent.

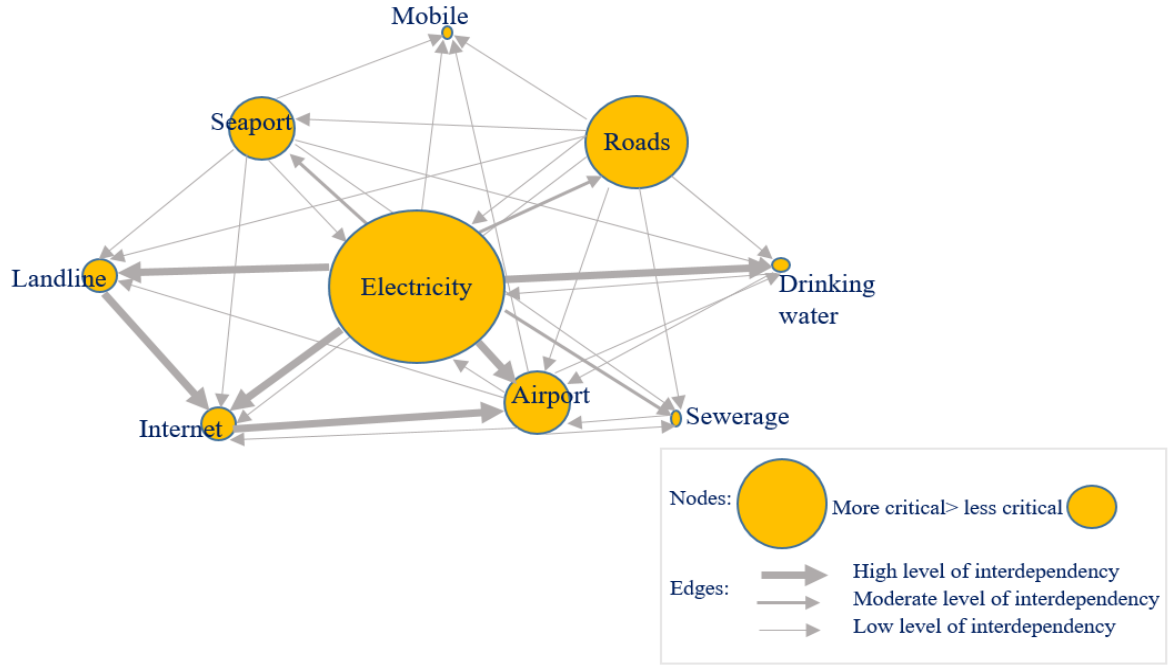
	Electricity	Drinking water	Sewerage	Mobile/3G/4G	Landline	Internet	Roads	Ports	Airports
Electricity		1	0	0	0	0	1	1	1
Drinking water	3		0	0	0	0	1	1	1
Sewerage	2	0		0	0	0	1	1	1
Mobile/3G/4G	1	0	0		0	0	1	1	1
Landline	3	0	0	0		0	1	1	1
Internet	3	0	0	0	3		1	1	1
Roads	2	0	0	0	0	0		0	0
Ports	2	0	0	0	0	0	1		0
Airports	3	1	1	0	0	3	1	0	

Interdependency level : Null Low Moderate High

**Figure 9.** Interdependency matrix of Saint-Martin's CI networks.

### 4.3 Integrating interdependencies for a systemic and efficient CI recovery planning

The obtained information from above analyses were used as input to build Saint-Martin's CI network-of-networks via a network-based model. The obtained CI network-of-networks is presented in figure 10 below. This network has a total of 9 nodes/CIs, and 33 edges implying 33 interdependency relations between the CI. The analyses of the network's topology and the nodes' strength  $s_i$  (or weighted vertex degree) have revealed the CIs' degrees of criticality in the network-of-networks. In fact, a node's out-strength, is the total weight of its outgoing connections, indicating herein that other CIs require this CI's service in order to operate or recover.



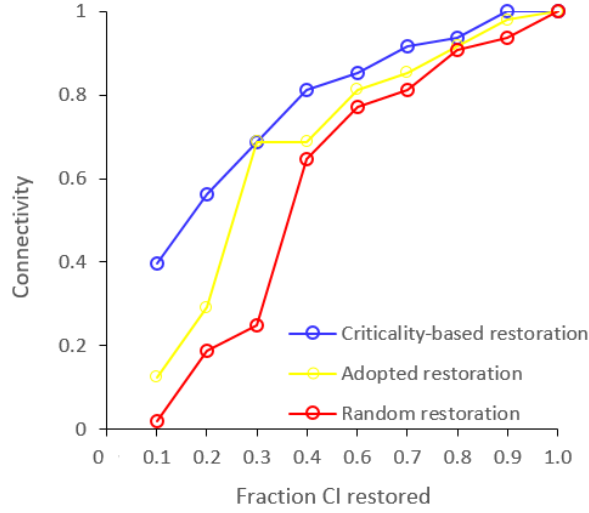
**Figure 10.** Saint-Martin's CI network-of-networks.

A criticality-based restoration strategy is set according to the uncovered strength  $s_i$  of each CI. The criticality-based restoration strategy  $R_{optimal}$  (equation 7) is written as a sequence of CI restored at time step  $t_{0+x}$  with  $1 \leq x \leq N$  the total number of CI, with CI being restored in descending order of their out-strength centrality.

$$R_{optimal} = \{Electricity^{t_0+1}, Roads^{t_0+2}, Airport^{t_0+3}, Seaport^{t_0+4}, Landline^{t_0+5}, Internet^{t_0+6}, Drinking\ water^{t_0+7}, Sewerage^{t_0+8}, Mobile^{t_0+9}\}$$

Equation 7. Criticality-based CI restoration strategy proposed for Saint-Martin.

The CI network-of-networks functionality/connectivity was then evaluated following different restoration strategies (figure 11). A worst-case scenario like Irma is considered, where all CI networks are damaged and need to be restored. CI were then added back into the network one by one and following: 1) a random restoration (random sequence of restored nodes), 2)  $R_{adopted}$  (equation 6) considered as the reference strategy adopted after Irma overlooking CI interdependencies and following a silo-based approach and 3)  $R_{optimal}$  (equation 7) considered as the targeted restoration in which CI are restored in descending order of their out-strength centrality. The CI network-of-networks functionality/connectivity was evaluated after each computation of nodes integration to the network at time step  $t_{0+x}$ . The three restoration simulations revealed different effects on the connectivity (considered as the functioning/functionality) of the network-of-networks.



**Figure 11.** The change in connectivity as function of CI restoration

The computational results showed that following a criticality-based restoration strategy  $R_{optimal}$  the network-of-networks's connectivity reaches 40% just after the first restored node (i.e., the electricity). The connectivity results when the third CI restored in  $R_{adopted}$  and  $R_{optimal}$  are overlapped. This can be explained by the fact that in the adopted restoration scenario the recovery times for the electricity and road networks were relatively short, which made it easier to get the rest of the networks back into operation. If it wasn't the case, the recovery patterns would have had a completely different form. However, differences start to appear after the third CI is restored. The total connectivity of the CI network-of-networks is reached only after the restoration of the seventh CI for the criticality-based restoration. While for both the random and adopted restorations, the total connectivity is not reached before the restoration of all CIs. In practice, enhancing recovery speed is a priority for decision-makers for cost and time saving. Reaching the total connectivity faster implies a faster recovery of the system (i.e., shorter CI failures duration which in turn indicates less economic losses). Hence, these first results showed that the recovery process is estimated to be faster if interdependencies were considered.

The results of the criticality-based restoration also indicated that the selection and restoration of some nodes/CI can play a vital role in regaining the network's connectivity. The restoration of central/critical nodes should be prioritized for a faster and more organized recovery, and for risk mitigation. Prioritization can involve repair priorities and prioritized resources allocation strategies. The electricity network is observed to be the most critical, the one on which the largest number of networks depend. The electricity network is thus considered to be the key CI to impede/or boost recovery of other networks and even of the entire island. Therefore, improving the resilience of the electric network will affect that of other dependent systems and will lead the way to an improved overall CI network-of-networks in Saint-Martin's island. Limiting the dependency to the electric network can also increase the network-of-networks recovery's pace. Power plants require demineralized water for the restart of their power generators. This interdependency can be decreased by the creation of redundancy through the installation of water storage tanks inside or near the power plants. Moreover, developing redundancy (installation of back-up systems as power generators) in terms of electricity supply for the rest of the CIs can be a solution to reduce delays in recovery. The road network, seaports and airports were also observed to be critical and the prioritization of their restoration has a considerable impact on the recovery of the network-of-networks. Indeed, the insular character of Saint-Martin as well as its small surface hamper the direct availability of the different resources (human, technical, etc.) needed for services restoration. Consequently, the criticality of transportation networks is of a significant level. To decrease the criticality of transportation networks, anticipation and planning are needed to make all the required resources available before the occurrence of a hurricane. On the other hand, the mobile network has shown to be relatively isolated, implying that this network would undergo minimal negative impacts when other CI are inoperable and delays in its restoration would not have repercussions on the network-of-networks.

## 5 Conclusion

The role of CI interdependencies during recovery is often understated and service restoration plans are generally conducted in isolation. This paper came in an attempt to fill this gap by investigating the influence of CI interdependencies on the restoration process and the importance of their integration. Real-world data about daily restoration rates of 15 CIs was collected to build service restoration curves over a period of 28 months (medium- to long-term recovery). The proposed methodology, adopting a holistic “network-of-networks”-based approach and statistical modeling, tested the efficiency of a criticality-based joint restoration strategy. The CI networks of Saint-Martin in the face of Irma, a major hurricane, were chosen as case study. The insular case of Saint-Martin added more criticality to the CI networks studied in this paper and offered a simple example (simplified network-based model using the graph theory).

Relying upon sequencing CI restoration based on their level of interdependency, a joint restoration strategy was found to be efficient in terms of rapidly restoring connectivity for the entire CI network-of-networks. *The outcomes of this study proved that recognizing and considering interdependencies in a well-coordinated restoration strategy (schedule planning and organized resources allocation) is necessary for completing the conventional silo-based/decentralized CI-by-CI restoration approach. It is believed that the systemic restoration strategy improves the resilience of CI networks and thus leads to a more resilient community.* For the case of Saint-Martin’s island, the electric network was found to be the most critical network since it can affect the service disruption of several networks and the recovery of the whole island. This result implies that the decision-makers should put more emphasis on improving the resilience of the power system to reach faster recovery and build systemic resilience in Saint-Martin’s island. The results also highlighted that to achieve faster recovery, pre-positioning and preparedness strategies for resources allocation should be considered. More repair crews and resources should be allocated for the recovery of the electric and transportation networks.

The adopted method, presenting a simplified network-based model, is subject to some limitations. Future research perspectives to overcome these limitations and better reflect the CI’s service restoration process in reality include: 1) the development of a facility-based or even component-based model, 2) including the restoration duration of each component and the demand for resources, 3) accounting for back-up strategies (power generators, water storage, etc.) and investigating the interaction effects of multiple factors on restoration resource allocation, and 4) coupling graph theory with other methods (e.g., object-oriented models or Petri net) to address possible recovery in deadlock situations. Uncertainties would also be taken into account (e.g., availability of repair crews, competence and proficiency of crews, budgeting, weather conditions, etc.) especially in unique situations such as a pandemic crisis like COVID-19. Further work is also suggested to conduct more direct evaluations of the proposed restoration strategy, such as possible time saving and cost saving, if precise and satisfactory data would be provided.

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