University of Groningen

Contextualizing resilience to critical infrastructure maintenance supply networks

Scholten, Kirstin; van Donk, Dirk Pieter; Power, Damien; Braeuer, Stephanie

Published in:
Supply Chain Management: an International Journal

DOI:
10.1108/SCM-02-2022-0078

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2023

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Scholten, K., van Donk, D. P., Power, D., & Braeuer, S. (2023). Contextualizing resilience to critical infrastructure maintenance supply networks. *Supply Chain Management: an International Journal*, *28*(7). https://doi.org/10.1108/SCM-02-2022-0078

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 01-11-2023

Contextualizing resilience to critical infrastructure maintenance supply networks

Kirstin Scholten and Dirk Pieter van Donk
Department of Operations, Faculty of Economics and Business, University of Groningen, Groningen, The Netherlands
Damien Power
Department of Management and Marketing, The University of Melbourne, Melbourne, Australia, and
Stephanie Braeuer
Department of Operations, Faculty of Economics and Business, University of Groningen, Groningen, The Netherlands

Abstract

Purpose – To be able to continuously provide affordable services to consumers, managers of critical infrastructure (CI) maintenance supply networks have to balance investments in resilience with costs. At the same time, CI providers need to consider factors that influence resilience such as the geographical spread or the location of the network. This study aims to contextualize supply chain resilience knowledge by exploring how maintenance resource configurations impact resilience and costs in CI supply networks.

Design/methodology/approach – An in-depth longitudinal single case study of a representative CI provider that has centralized its maintenance supply network is used. Data were collected before and after the change to evaluate the effect of the changes on the maintenance supply network.

Findings – This study shows that in this specific CI maintenance context, structural resource choices such as the quantity or location of spare parts and tools, the creation and exploitation of tacit knowledge and staff motivation impact both resilience and costs due to geographical spread, network location and other network properties.

Originality/value – This study extends general supply chain resilience knowledge to a new setting (i.e. CI) and shows how existing insights apply in this context. More specifically, it is shown that even in engineered supply networks there is a need to consider the effect of human agency on resilience as the creation and exploitation of tacit knowledge are of immense importance in managing the network. In addition, the relationship between normal accidents theory and high reliability theory (HRT) is revisited as findings indicate that HRT is also important after a disruption has taken place.

Keywords Resilience, Normal accidents, High reliability, Single case study, Maintenance, Critical infrastructures

Paper type Case study

Introduction

It is widely acknowledged that failure in critical infrastructure (CI) supply networks (e.g. water and energy) is not an option (Boin and McConnell, 2007a; Cedergren *et al.*, 2018). Even minor breakdowns can impact large numbers of people and potentially lead to high social costs in terms of human life, the environment or economic markets when failures cascade with ripple effects on regional, national or international scale (Cantelmi *et al.*, 2021). Hence, building resilience into CI networks is important (Cantelmi *et al.*, 2021; Van den Adel *et al.*, 2022) as it reduces the impact of disruptions e.g. recovery time (Tukamuhabwa *et al.*, 2015). Prior research provides general insights on how supply networks can be resilient via redundancy, agility, collaboration and flexibility (Ali *et al.*, 2017). However, there is a knowledge gap in relation to context specific attributes of CI networks such as the geographical spread, operational history or the access to the network (e.g. pipelines underground; Boin and McConnell, 2007a; Ouyang, 2014), that might influence the creation of resilience in CI supply networks (Dittfeld *et al.*, 2022; Linnenluecke, 2017; Scholten *et al.*, 2020).

Beyond the specific CI network attributes that might influence building supply network resilience, there is pressure on CI organizations to keep costs low (Blokus and Dziula, 2021). Hence, organizations need to balance investment in resilience (e.g. redundancy and IT systems for

The current issue and full text archive of this journal is available on Emerald Insight at: **https://www.emerald.com/insight/1359-8546.htm**

Supply Chain Management: An International Journal
28/7 (2023) 1–14
Emerald Publishing Limited [ISSN 1359-8546]
[DOI 10.1108/SCM-02-2022-0078]

Received 25 February 2022
Revised 20 July 2022
11 November 2022
9 January 2023
Accepted 12 January 2023

increased agility; Christopher and Peck, 2004) with the costs of service provision. Resource decisions that affect both resilience and costs in CI supply networks are usually associated with maintenance activities (Hemme, 2015) as proper maintenance guarantees the functioning of CIs (Blokus and Dziula, 2021) and determines, for example, the length of downtime. Accordingly, we consider the configuration of physical, manpower and information resources in a maintenance supply network (Hastings, 2015; Tsang, 2002) and their impact on costs as a key part of contextualizing resilience knowledge to the CI setting.

There is a general assumption that the "right" configuration of resources can bring significant benefits to these networks. At the same time, however, what exactly that "right" configuration entails is not known and likely to be context specific (Linnenluecke, 2017). Furthermore, while optimization of costs related to ensuring resilience seems to be one of the most important challenges in current research (Blokus and Dziula, 2021), optimization of other benefits is equally complicated (Garg and Deshmukh, 2006). We do not aim to optimize or find the "right" resource configurations, but to provide insights into ways structural and human resource configurations influence resilience and costs in a specific CI setting. Accordingly, we apply an in-depth representative and longitudinal single case study (Yin, 2009) within the context of a water supply organization in The Netherlands and ask: *How do maintenance resource configurations influence resilience and costs in CI supply networks*?

This study makes three key contributions. First, we contribute to contextualizing the concept of supply chain resilience as called for by Scholten *et al.* (2020). This study shows that building resilience in CI is influenced by the geographical spread of the network that creates trade-offs between the logistics of resources and the quantity of resources/number of storage locations. Furthermore, our study contributes to the field of supply chain resilience by highlighting the importance of human agency for the resilience of engineered supply networks (Park *et al.*, 2013; Yu *et al.*, 2020). Specifically, it is shown that in CI, the maintenance resource network needs to be designed in a way that facilitates the creation and exploitation of tacit knowledge, an insight that also provides guidance for CI managers. Finally, we contribute to the understanding of the relationship between normal accident theory (NAT) and high reliability theory (HRT; e.g. Shrivastava *et al.*, 2009). We find that due to the specific CI network characteristics that lead to disruptions based on NAT logic, HRT principles are not only important to avoid disruptions, but particularly important in responding to and solving problematic events.

Literature review

CI are large technical supply networks that provide services such as energy, transportation, water or communication, imperative to support everyday life in modern economies and society (Cantelmi *et al.*, 2021). Services provided by CI networks are often nonsubstitutional to the public and mutually interdependent (Ouyang, 2014; La Porte, 1996). Therefore, the breakdown of any CI can cause serious problems (Boin and McConnell, 2007b; Cedergren *et al.*, 2018). In the CI context, resilience is understood as the adaptive capability to "prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations" (Ponomarov and Holcomb, 2009, p. 131). Although most disturbances cannot be fully anticipated (Scholten *et al.*, 2019), resilience allows an organization to effectively manage events while maintaining efficiency and ultimately reducing recovery time (Tukamuhabwa *et al.*, 2015). In engineered systems such as CI, rapid recovery is essential and a fundamental indicator of the level of resilience (Yu *et al.*, 2020). Therefore, resilience needs to be designed into such a system (Christopher and Peck, 2004) by focusing on redundancy, agility, flexibility and collaboration [the four most cited resilience elements (Sawyerr and Harrison, 2019; Tukamuhabwa *et al.*, 2015)]. Redundancy relates to keeping some resources in reserve to be used in case of a disruption (Ali *et al.*, 2017). As such, redundant resources (e.g. inventory or capacity) lower the likelihood of a disturbance affecting the entire network (Wiengarten *et al.*, 2017) as they can be invoked when there is a supply or demand shortage (Christopher and Peck, 2004). Agility helps to reduce the impact of a disruption (Ponomarov and Holcomb, 2009) by means of visibility and velocity (Tukamuhabwa *et al.*, 2015). More specifically, visibility creates a transparent view throughout the supply network highlighting changes in key factors such as inventories, supply or demand (Jüttner and Maklan, 2011). Velocity enables quicker responses to and recovery from disruptions (Christopher and Peck, 2004). An efficient response via velocity can be complemented by an effective response to sudden changes via flexibility (Pettit *et al.*, 2013, 2019). Flexibility can be achieved by contracts that allow for modifications in delivery schedules, manufacturing facilities that can be used to produce multiple products or a multi-skilled workforce (Ali *et al.*, 2017). Finally, collaboration allows supply chain entities to work together effectively for mutual benefits (Pettit *et al.*, 2013; Van den Adel *et al.*, 2022). This can entail information sharing, joint knowledge creation, decision synchronization or incentive alignment that help in the preparation for, response to or recovery from disruptions (Scholten and Schilder, 2015). In general, resilience elements can be interrelated (Dube *et al.*, 2022), and their composition or emphasis differs depending on the context they are deployed in Ali *et al.* (2022) and Dittfeld *et al.* (2022). Further discussion and elaboration of supply chain resilience can be found in reviews by Sawyerr and Harrison (2019) or Tukamuhabwa *et al.* (2015).

Resilience in critical infrastructures

Building resilience into CI networks requires specific attention due to the geographic spread of the network, its location and interactive complexity as well as tight coupling (Boin and McConnell, 2007a; Ouyang, 2014; Van den Adel *et al.*, 2022). CI networks are often structurally and geographically diverse rendering them vulnerable to a large variety of disturbances (Schulman *et al.*, 2004). They are typically continuously operational and as such, can be the product of an aggregated operational history over a span of 50 or 100 years leading to an idiosyncratic patchwork of equipment and organizational units with their own peculiarities, materials, projects and ways of working (Almklov and Antonsen, 2014). Furthermore, the high geographic spread of CI limits visibility and makes predicting consequences of a disruption and responding more difficult (Boin and McConnell, 2007b).

The location of the network [such as pipelines or cables in the ground (Boin and McConnell, 2007b; Ouyang, 2014)] can obscure visibility regarding condition of components and requires having to dig to reach disrupted parts while paying attention to other, physically related infrastructures such as buildings or roads (Boin and McConnell, 2007b). Here a constraint is that the history, heterogeneity and/or invisible underground nature of the network are hard to document sufficiently (Almklov and Antonsen, 2014).

CI networks also exhibit high interactive complexity (e.g. interactions of numerous workers, pipelines and the environment with low visibility) and tight coupling (e.g. time-dependent processes, invariant sequences of operations; La Porte, 1996). There are two major theories that focus on accident prevention that help to understand these system properties of interactive complexity and tight coupling relevant to CI (Cedergren *et al.*, 2018): NAT and HRT. NAT takes a system design and risk mitigation perspective and predicts that disruptions are normal in systems with high interactive complexity and tight coupling (Perrow, 1984; Wiengarten *et al.*, 2017). The underlying reasoning is that the structure of a system creates barriers to the identification, comprehension and correction of variations in results (Skilton and Robinson, 2009) so that an incident (or disruptions) at lower system levels can trigger chain reactions at higher levels with potentially catastrophic effects (Chowdhury and Quaddas, 2016; Wiengarten and Longoni, 2018). To deal with complex interactions, NAT suggests decentralization to facilitate a real-time response to unanticipated interactions locally (Leveson *et al.*, 2009). In contrast, for tight coupling NAT theory suggests centralization to enable visibility in the system (Shrivastava *et al.*, 2009). Yet, simultaneous centralized and decentralized network configurations would appear to be incompatible (Shrivastava *et al.*, 2009). Hence, accidents will occur and NAT posits that it is only possible to mitigate, reduce or minimize damage (Hillmann, 2021). HRT takes a different approach and suggests, that disruptions are preventable (in complex and tightly coupled systems) if organizations allow for decentralized decision making in combination with investing in redundancy (Hovden *et al.*, 2010; Sawyerr and Harrison, 2019; Wiengarten and Longoni, 2018). Hence, two theories focus on disruptions at different points of time: HRT focuses on processes related to the period leading up to the point of accident and NAT identifies the key elements of organizational structure and circumstances at the point of time of an accident (Shrivastava *et al.*, 2009).

The above-discussed CI network attributes make it hard to anticipate possible disruptions precisely (Skilton and Robinson, 2009) and, therefore, to build resilience (Cantelmi *et al.*, 2021). Accordingly, Dominguez *et al.* (2009) propose that organizations managing CI should focus on improving organizational processes. This suggests that CI resilience could be closely linked to the management of the maintenance supply network (Blokus and Dziula, 2021): ongoing maintenance helps to reduce business risks by hazard elimination, ensures the ability of continuous performance and decreases the length of disruptions (Marais and Saleh, 2009). However, supply network maintenance in CI provision has received minimal attention, despite the risk of a disruption being greater [than (say) from an occasional disaster (Hemme, 2015)] if maintenance is not properly managed.

Management of maintenance supply networks

Maintenance in supply networks entails all technical and administrative actions intended to prevent disruptions or to restore the function of the network to a desired operational condition after being disturbed (Balzer and Schorn, 2015; Saleh and Marais, 2006). Strategically, maintenance relates to inputs, the design of the maintenance process (management of the maintenance functions, structure of tasks and maintenance policies) and the support system (design of the supporting infrastructure; Blokus and Dziula, 2021; Tsang, 2002), which includes resource decisions such as the location of warehouses and inventory or the availability of machines. In this research, we address the management of resources in the maintenance supply network [physical, manpower and information resources (Hastings, 2015; Tsang, 2002)] which are particularly important for network resilience (Christopher and Peck, 2004; Schulman and Roe, 2007). While previous literature on maintenance management focuses on analytical optimization models and techniques, scheduling, performance measurement, information systems and policies (Garg and Deshmukh, 2006), there is limited consideration of the configuration of resources. In fact, we could only identify five relevant sources that relate to the resource choices that have to be made in managing a maintenance supply network (Table 1).

In summary, the maintenance resource choices outlined in Table 1 can help an organization to become more resilient by choosing and positioning strategic surplus resources (Tukamuhabwa *et al.*, 2015). At the same time, redundant resources add to operating costs of CI providers and organizations also need to keep their service affordable (Blokus and Dziula, 2021). Furthermore, the maintenance supply network in itself represents a large proportion of cost for CI as it relates to thousands of kilometers of (underground) network with an operational history (geographically spread and network location) that is tightly coupled and interactively complex (network properties). While previous research points out that resilient networks should also be able to be efficient (Tukamuhabwa *et al.*, 2015), most research only considers efficiency versus resource redundancy trade-offs. Yet, as Table 1 outlines there is more to consider in making resource choices than the actual quantity of spare parts, tools or manpower. It also highlights the importance of logistics and the associated competences of the work force. Accordingly, this study investigates how maintenance resource configurations (Table 1) impact resilience (redundancy, agility, flexibility and collaboration) and costs in the context of CI supply networks (geographical spread, network location and properties).

Methodology

Approach and case selection

This study aims to provide an *understanding* of the dynamics of resilience within the specific CI maintenance supply network setting. In doing so, we use NRT and HRT to *explain* attributes of the supply network linked to the specific CI context. To accommodate understanding and to facilitate explanation we

Table 1 Maintenance resource types and their related key management choices

Resource	Key management choices	Elements of key choices
***Manpower*:** **executive element in physical repair (Balzer and Schorn, 2015)**	Composition	– Competence level (Balzer and Schorn, 2015; Kelly, 2006) e.g. education and tacit knowledge – Defined work roles (Hastings, 2015; Kelly, 2006); specialized versus cross-trained (Hastings, 2015; Hopp, 2008; Kelly, 2006; Pintelon and Gelders, 1992) – Morale, motivation and attitude (Kelly, 2006; Pintelon and Gelders, 1992)
	Quantity	Size of workforce (Balzer and Schorn, 2015; Hastings, 2015; Kelly, 2006; Pintelon and Gelders, 1992)
	Localization	Central versus decentral; dedication to the maintenance of a single plant, area or unit type or several (Hastings, 2015; Kelly, 2006)
	Logistics	Movement of maintenance staff (Kelly, 2006)
***Spare parts*:** **consumable items that have a significant influence on the operability, stability and costs within an infrastructure system (Balzer and Schorn, 2015)**	Quantity	Inventory Policy (Kelly, 2006; Pintelon and Gelders, 1992)
	Localization	– Function and number of stores (Hastings, 2015; Kelly, 2006) – Central versus decentral (Hopp, 2008)
	Logistics	Movement of spare parts (Kelly, 2006)
***Tools*:** **nonconsumable items used to perform or facilitate work (Balzer and Schorn, 2015; Kelly, 2006)**	Quantity	Inventory policy (Kelly, 2006; Pintelon and Gelders, 1992)
	Localization	– Function and number of stores (Hastings, 2015; Kelly, 2006) – Central versus decentral (Hopp, 2008)
	Logistics	Movement of tools (Kelly, 2006)
***Information*:** **documents, catalogues, manuals or drawings that might facilitate maintenance work (Kelly, 2006)**	Purpose	– Reference before work is carried out e.g. manuals (Hastings, 2015; Kelly, 2006; Pintelon and Gelders, 1992) – Instruction to be consulted before work is carried out (Hastings, 2015; Kelly, 2006; Pintelon and Gelders, 1992) – Control i.e. storage and analyses of historical data, performance and costs (Hastings, 2015; Kelly, 2006; Pintelon and Gelders, 1992)
	Availability	– Electronic versus paper based storage (Kelly, 2006) – Centralized versus decentralized storage (Kelly, 2006)

make use of the (contextualized) explanatory power of case study research (Welch *et al.*, 2011; Yin, 2009). Case study methodology is known to be able to deal with complex phenomena as well as difficulties arising from unclear boundaries between the context and phenomena as in the problem at hand (Yin, 2009). More specifically, this study examines the maintenance supply network (unit of analysis) of a major water production and distribution company in The Netherlands. The chosen case can be considered representative of the sector (informative for similar CI providers) as well as longitudinal (investigation of change over time), with either reason being sufficient for conducting a single case (Yin, 2009).

The case is representative, firstly, because similar to other CI providers its main focus is on the satisfaction of customers and providing value for money while being controlled by representatives of elected governmental entities. At the same time, this organization strives for a good balance between quality of water and price evident in the fact that it has been one of the cheapest in price for many years (compared nationally with other regional providers) even though developments such as a dry summer in 2018 have required additional investments in research and assets. Second, the network of the water supply company consists of over 5,000 km of pipeline underground and can therefore be considered to have a broad geographical spread and to be diverse (servicing remote farms as well as densely populated cities). Hence, the focus on value for money in a geographically spread network provides an ideal setting for studying how a maintenance supply network can be managed in the specific context of CI networks.

Furthermore, the case was identified as appropriate because the organization had decided to make structural resource changes in its maintenance supply network. In particular, one central warehouse and two satellite warehouses, each with their own organizational structure, were merged into one central warehouse with one central organizational structure. While this affected the location of spare parts, tools and manpower, other resource choices with regards to the maintenance supply network (Table 1) also had to be made to facilitate the change. In changing this structure, the organization aimed to reduce costs (centralization of inventory) and increase resilience (centralization of the organizational structure). Although asset re-structuring on this scale does not happen often, it is something that many companies undergo over time and, hence, presents a learning opportunity for similar CI providers. Furthermore, it is clearly linked to the problem we were investigating.

Data collection

Data were collected during 2015–2016 (before restructuring) and in 2019 (after restructuring) from multiple sources via multiple methods for triangulation purposes (Yin, 2009). An overview of the data collected is provided in Table 2.

Table 2 Overview of methodological process

Process	What	How		
Theoretical exploration	*Literature review*	Exploration and determination of resilience operationalization and aspects of contextualizing resilience to the CI setting. Keywords used: supply chain resilience, risk, disruption, CI, NAT, HRT; from there on snowballing		
Empirical exploration	*Data collection*	3 Focus Groups	Asset Manager, Maintenance Team Leader North, Maintenance Team Leader East, Maintenance Planner East, Maintenance Planner North	60 min
			Asset Manager, Lean Facilitator, Head of Maintenance Distribution, Head of Purchasing and Logistics, Maintenance Team Leader East	90 min
			Asset Manager, Head of Maintenance Distribution, Head of Purchasing and Logistics	60 min
		4 Interviews	Asset Manager	120 min
			Head of Maintenance Distribution, Head of Purchasing and Logistics, Head of Water Supply	About 60 min each
	Data analysis	Focused on understanding the context and objectives of the maintenance supply network and its re-organization. Based upon these insights, an interview protocol was developed for the next step, we were able to identify all stakeholders that were important for the main data collection and we decided to focus on re-organization on the level of maintenance resources		
Theoretical elaboration	*Literature review*	Confirmation of the chosen resilience conceptualization. Conceptualization of maintenance resource as main focus of the re-organization		
Deriving findings	*Data collection*	16 Semistructured interviews	Asset Manager I, Asset Manager II (2×), Head of Maintenance Distribution (3×), Head of Purchasing and Logistics (3×), Maintenance Team Leader (2×), Maintenance Staff North, Maintenance Staff East, Maintenance Planner, Maintenance Engineer	About 60 min each
		Archival data	Flow diagrams, presentations, reports, memos, strategic policies e.g. protocol of uniform registration of failures, cost reporting maintenance, order advice report	116 pages
		1 Focus group	2 Maintenance Staff North, Maintenance Team Leader North	120 min
		Field observation	2 Maintenance Staff North	120 min
		5 Follow-up interviews	Asset Manager, Head of Maintenance Distribution, Head of Purchasing and Logistics, Maintenance Team Leader North, Maintenance Team Leader East	About 60 min each
	Data analysis	As described in the data analysis section of this paper		
Validation	*Data collection*	Focus group	Asset Manager, Head of Maintenance Distribution, Head of Purchasing and Logistics, Maintenance Team Leader North, Maintenance Team Leader East	60 min
	Data analysis	The focus group provided additional explanations and context for some examples and validated our findings		
Reflection	*Data collection*	Semistructured interview	2 Maintenance Staff	45 min
		Focus group	New Head of Maintenance Distribution 2 Schedulers	50 min
	Data analysis	Followed the same procedures as for the main interviews and confirmed findings after the re-organization had actually taken place		

Accordingly, to understand the context and objectives of the planned maintenance supply network resource changes, we conducted three focus group interviews with senior stakeholders, identified by the organization as being affected by the changes. The open discussions during the focus group interviews not only allowed us to gather information on aspects that needed to be considered with regards to the management of resources in the maintenance supply network, but also facilitated the identification of other key stakeholders who could provide information in further interviews (e.g. Head of Water Supply, senior fitters and engineers). At that stage, we had identified all relevant stakeholders within the company and focused on those that had 10 years or more of work experience. Following these initial focus groups, we conducted four exploratory interviews with decision makers in senior and strategic positions. Different questions were asked depending on the function of the interviewee to understand the structure of the maintenance resource network before the change. For example, questions to the Head of Purchasing and Logistics related to how inventory is planned in the central and satellite warehouses, what spare parts are kept in stock, the amount of manpower at the different locations or what the biggest challenges in the maintenance supply network are. The focus group and exploratory interviews provided initial insights into the main resource choices that could be made besides the relocation of spare parts, tools and manpower due the centralization of the warehouse and organizational structure. Such choices related to e.g. logistics, quantity and role division of manpower.

To further understand the effect of the different resource configurations on resilience and cost, we conducted 16 semistructured interviews with the previously identified key stakeholders (sometimes interviewing a key person twice or even three times to clarify points and gain further insights).

We asked: "How do you use resources to (1) anticipate and prepare for and (2) respond to disruptions?," "What influences your ability to (1) anticipate and be prepare and (2) respond?," "How would the planned restructuring of the maintenance supply network affect (1) the preparedness and (2) the response of the network to disruptions considering the different resources?," "What specific changes in resource structure would be necessary and why?" and "Can you reflect on different trade-offs between costs and resilience that will have to be made in re-structuring the resource network?." Throughout the interviews, we probed for specific examples of situations. To validate the insights gathered up to this point we conducted a follow-up focus group.

Finally, we went back to the organization in 2019 after the implementation of the network change to gather insights on the outcomes of the re-structuring. In addition to objective data on tools and manpower resources that we gathered, we interviewed the relevant maintenance staff personally to know how they were affected by the change. Accordingly, we conducted one interview with two senior fitters and a focus group interview with the new Head of Maintenance Distribution and the two main schedulers. Questions focused on reviewing results derived from the interviews in 2015–2016 and reflecting on the implications of the implemented changes in terms of cost and resilience.

Data analysis

A data base was developed to organize the large amount of data gathered. Following the process of qualitative data analysis described by Miles and Huberman (1994), interview transcripts and archival data were first reduced to sentences and paragraphs that were relevant for this study. After attaching descriptive codes to the reduced data, we went through two cycles of coding in line with the aim of this study. First, to explore how a maintenance supply network can be managed in the specific context of CI networks we deductively coded all data for the CI characteristics of geographical spread, network location and network properties, and the maintenance resources (manpower, spare parts, tools and information) as well as the resource choices as per Table 1. The initial descriptive codes were then further refined to reflect the causal mechanisms that influenced each resource choice based on the specific CI network characteristics. As not all influences could be described by the CI characteristics, explanations linked to legislative requirements and the company philosophy were derived inductively.

Second, we investigated how the maintenance resource configurations impact resilience and costs. Accordingly, we deductively coded the data for the resilience elements i.e. flexibility, collaboration, redundancy and agility (visibility, velocity) and costs. Next, the data were juxtaposed to identify the impact of resource choices on cost and resilience simultaneously. To compare different resource choices and identify relevant patterns we started to map out relationships (i.e. how choices influence cost and resilience). Cost outcomes were linked to the quantity of spare parts, tools, manpower and/or logistics (e.g. the amount of driving required) and as such it was possible to code for an estimated increase or decrease of costs per resource. In relation to resilience, the influence of the resource configurations was less straight forward. Therefore, we refrained from drawing conclusions on whether resilience was increased or decreased, but concentrated on underlying factors that could influence resilience such as an increase in redundancy. Furthermore, it became apparent that in some instances resilience was dependent on manpower resource configurations. In particular, tacit knowledge and motivation kept emerging from the data as important factors for resilience. While tacit knowledge was linked to collaboration, motivation could not be coded for any resilience aspect and as such, we could not ascertain a concrete influence of the motivation of manpower resources in relation to cost or resilience. We used the data collected in 2019 to confirm and extend the initial results with further detail on the actual outcomes. As such, the interview data were coded in the same way. Searching for explanations of the results we formulated cause and effect propositions wherever possible. At the same time, the above-mentioned aspects related to the manpower resources could not be converted into a proposition. Instead, they provided an interesting new insight in the form of a causal mechanism as will be outlined in the discussion section.

Throughout our data analysis, we paid attention to observing the quality criteria for qualitative research. More specifically we did the following (adapted from Reuter *et al.*, 2010; Yin, 2009):

- Reliability: developed a case study protocol (design); selected a relevant and longitudinal single case (case selection); developed a case study data base, shared the interview protocol with interviewees prior to the interview and let all interviewees review the interview transcripts (data collection); and had authors involved in the paper that were not involved in the actual data collection (data analysis).
- Internal validity: established theoretical foundations and variables prior to the data analysis whenever possible (design); noted the case selection in the case study protocol (case selection); interviewed multiple informants from different functions and levels within the organization (data collection); and used different sources of data (archival data, interviews etc.) to triangulate findings whenever possible, presented all findings to the case company and performed pattern matching and explanation building by two researchers independently (data analysis).
- Construct validity: used established operationalization of constructs (design); had two interviewers for each interview (data collection); and discussed all (intermediate) results with the case company representatives (data analysis).
- External validity: established clear description of the case firm, context and situation (case selection); and aimed to develop analytical generalizability i.e., theoretical insights idiosyncratic to the specific context and not generalizable to populations or universes (data analysis).

The overall methodological process is depicted in Table 2.

Findings

Pivotal to the analysis of the maintenance, supply network is the decision to centralize the warehouse, planning and organizational structure (location of spare parts, tools and manpower). Hence, these key decisions form the origin for all other resource choices made in the maintenance supply network, considering investments as sunk costs. Following, we first outline regulative and company influences followed by influences from the CI context on the management of the maintenance supply network (Table 3). We then present the findings in relation to how maintenance resource configurations impact resilience and costs based on the resource changes in the maintenance supply network (Table 3).

Regulative influences

By law, water suppliers in The Netherlands have to solve disruptions within 24 h for households and "disturbances have priority over planned maintenance and projects" (Head of Maintenance Distribution). As there "is not a lot of time to react, having the materials determines the response" (Head of Purchasing and Logistics). Hence, availability of spare parts is critical, leading to our finding that decisions in sourcing spare parts and their inventory management are always made on the basis that "price is important, availability is more important" (Head of Purchasing and Logistics). As a result, 99.9% of required material is held in stock and only material that can be purchased within 24 h is ordered. Furthermore, we find collaboration with other water supply companies in case materials cannot be sourced in time or are not in stock, for example "we call other water companies in case of big leakages"

Table 3 Findings influencing factors and outcomes

Resources	Resource decisions	Influencing factors	Cost	Resilience
Spare parts and tools	*Quantity*	• Availability and quality > price *(regulations and company philosophy)* • Collaboration with other water supply companies *(regulations)* • Variety of materials required/ used *(geographical spread and network properties)* • Different levels of inventory throughout year *(network properties)* • Hire tools *(network location and geographical spread)*	Reduced costs of spare parts: inventory pooling	• Increased visibility and redundancy of spare parts: better overview of the overall availability of stock in one warehouse rather than three • Decreased visibility and redundancy of tools: availability declined as there are less opportunities for return (see also logistics)
	Logistics	NA	Increased costs: larger distances (fuel consumption)	Decreased velocity: spare parts and tools further away
Manpower	*Quantity*	• Keep spare capacity *(regulations)* • Decentralized spare capacity throughout network *(geographical spread)* • Different amount of staff on standby throughout the year *(network properties)*	Reduced costs: decreased amount of staff	No change: no capacity problems
	Logistics	Large driving distances *(geographical spread)*	Increased costs: more driving (fuel consumption)	• Increased redundancy: start work from home • Decreased redundancy: more driving • No change in velocity: Average response time between a disruption registered by the call center and fitters reaching leakage = 1 h
	Composition/ Localization	• If disruption > 24-h decision rights shift from decentral to central *(regulations)* • Variety of competences needed *(geographical spread)* • Decentralized amenities → Provide extrinsic motivation *(geographical spread and network location)* → Knowledge exchange *(geographical spread, network properties)* • Decentralized decision rights *(geographical spread)*	Reduced costs: hiring of new, less experienced staff	• Decreased flexibility: not all fitters can do every job as new staff do not have all competencies yet • Increased flexibility: scheduling in one team including rotations over the geographical spread (competency development) • Increased collaboration: more tacit knowledge due to one planning domain and team • Reduced collaboration: less opportunities to exchange knowledge
			Reduced motivation due to changes in the localization	
Information	*Purpose*	• Instructions: Decentralized decision making, but centralized if disruption >24 h requiring a crises team and involvement of government *(regulations)* • Reference, instruction and control →Knowledge repository *(geographical spread, network location and network properties)* → Preventive maintenance costs are high *(network location)*	No change	No change
	Availability	Centralized: knowledge repository *(geographical spread and network properties)*	No change	No change

(Head of Purchasing and Logistics). In terms of manpower, the response time is enabled by scheduling fitters at 70–80% capacity throughout the week for projects and preventive maintenance. The redundancy in time allows for room in the schedule of each individual to respond to disruptions immediately if required.

The legal requirements with regards to solving disruptions within 24 h include further procedures such as the set-up of a crisis management team and close communication with the government in case the response time exceeds the acceptable time period. In addition, in such situations the autonomy to make decisions that usually lies with the individual fitters conducting corrective maintenance is shifted toward higher management. As such, the management of the disruption shifts from a decentralized to a centralized *locus*. This is in contrast to the normally high emphasis given to decentralized decision-making with no instruction on how to perform maintenance work (e.g. which tools to use).

Company philosophy

Tools and spare parts

The focus on service due to regulations is further evident in the company philosophy where quality and service are more important than costs. "Of course we try to get the costs as low as possible but it is not our main thing because we want to do a good qualitative job." (Maintenance Team Leader North). The importance of quality over costs of maintenance is also highlighted by other employees in the network such as the fitters and the Asset Manager who mentioned that "if there is more than one solution, we normally go for the best solution, the solution that lasts longest. So quality of the solution is first then speed, then delivery time and then costs." (Asset Manager I). We find that this might mean fixing problems temporarily to "then order the right material" (Head of Purchasing and Logistics) that allows for a higher quality solution. In addition, to ensure "that next time we do not have the same problem again" (Maintenance Team Leader North) better or more tools and spare parts might be purchased and/or hired.

Manpower

In terms of service, fitters "always try to solve disruptions as fast as possible" (Focus Group), not only due to legal requirements, but as we find, also on account of high intrinsic motivation. "The fitters always want to deliver water as soon as possible. They don't wait, don't waste time. They always want to provide the customer as soon as possible with water again, and then they always try to do their best" (Maintenance Team Leader North). This was also emphasized by the fitters themselves comparing doing maintenance with working on their own house and highlighting that "without us there is no water" (Focus Group).

Critical infrastructure influences

Tools and spare parts

Regarding the CI context, we find that network properties influence the occurrence of disruptions. Weather conditions (rain, drought, storm, wind or ice), farming and roadworks can cause incidents and highlight the interactive complexity between the environment and the supply network. In addition, we find that there are seasonal differences in the frequencies of disturbances: there is an increase during winter with frosty days and wind from the East, a decrease during summer vacation and then again an increase in August and September due to harvesting related traffic around pipelines. Accordingly, the water supply company has to increase its resilience at certain times of the year and does so by keeping additional stock of spare parts.

We also find that the network location influences the variety of spare parts needed as "[part of] the pipe system is more than 100 years [and there are] several and different kinds of material lying in the ground" (Head of Purchasing and Logistics). The water supply company tries to standardize material as much as possible not only to have less variety in stock (i.e. lower costs), but also because standard spare parts are available at short notice from suppliers. Yet, given the age of the network, using standardized spare parts is not always possible. Hence, there is a need to keep a larger variety of specific spare parts in stock to ensure availability "especially when the lead time is long" (Asset Manager I). At the same time, in relation to tools, we find that due to the geographic spread and the network properties, the variety of tools required is so large that not all can be kept in stock as it would entail large additional costs. Therefore, there are "contractors that support us with big equipment and operations" (Head of Maintenance Distribution), for example, cranes.

Manpower

For manpower resources, we find, similar to spare parts, that given the network properties and the pattern of disruptions over the year, more manpower is scheduled "when it is minus ten degrees. Then we know we get a lot of leakages on the water meters because they freeze. Then we prepare by having more people on stand-by [during nights]" (Head of Maintenance Distribution). Given the geographic spread of the network it was not possible to keep one person on stand-by for disruptions as it reduced the response time based on large driving distances. Instead, the water supply company schedules redundancy in capacity (see regulative influences) so that the closest fitter to a disruption can always go to fix it.

We also find that, given the geographical spread and network properties, fitters find close communication and face-to-face contact with other staff to be an important source of direct information as "you need to talk to the colleagues because at the job you must know what is happening. You need to see each other" (Fitter East) to build tacit knowledge. Hence, the (decentralized) localization of manpower determines the "responsiveness of this network. [Maintenance] processes are faster because they [fitters] are located nearer to the worksites and they know the region. So they have knowledge about the quality of the pipes." (Asset Manager I). We find that such tacit knowledge helps in responding to disruptions as it facilitates agility.

Furthermore, from a flexibility and velocity point of view and given the geographical spread and network properties, we find that the water supply company strives to develop a multi-skilled work force, as decisions on how to conduct corrective maintenance have to be decentralized, i.e. taken at the disruption location. Additionally, to "have a good mix of quality and price" supplementary professionals are hired in "for laying ground bricks for the pedestrian and when we have pipes that are in a garden we use professional gardeners" (Asset Manager I). As such, geographical spread, network location and properties also influence costs based on what competencies are available in house and which are outsourced.

Information

With regards to information and the CI context we find that given the geographic spread and network properties identifying and responding to disruptions can be difficult. As such, there is a "need to know where the location of the leakage is and we need to know how big it is" (Asset Manager I). The organization uses a geographic information system that provides references to fitters not only in terms of drawings of pipes and positions of valves, but also about special consideration in case the disruption is, for example, close to a hospital or pipes of other CI providers. These maps and points of reference are updated continuously by staff on their handheld computer when conducting preventive and corrective maintenance to build up a knowledge base of the different materials in the ground, the age and condition of the pipes and access points. As such, this information provides a centralized knowledge repository that can be used for reference, instruction and control and "enforce standards and knowledge" (Asset Manager I). This allows the organization to build up information over time that can help to understand and manage the geographical spread and network location characteristics and indirectly contributes to resilience. At the same time, however, conducting preventive maintenance still entails a lot of unknown factors as it might be difficult to assess the state of the underground pipes (no visibility) and preventive maintenance (i.e. digging) might even be harmful.

Outcome of resource choices in the maintenance supply network

Tools and spare part

It was anticipated that with the centralization of warehouses from three to one "the stock level we now [original layout] have can be lower" (Head of Purchasing and Logistics). The focus group interview in 2019 confirmed that pooling of inventory took place (reduced quantity of spare parts) leading to some cost savings as well as increased visibility "as there is more of an overview of the overall availability of spare parts now". While in the old configuration there seems to have been a difference between the two satellite warehouses with regards to availability of spare parts (redundancy) where in one "it [tools, spare parts] is always available" (Fitter North), in the other it "sometimes takes a little bit longer because some materials are not there" (Fitter East). The interview with the fitters and the focus group in 2019 confirmed that after the re-organization spare parts for conducting maintenance are available when needed. Accordingly, concerns that were voiced before the re-organization with regards to "when we come together and we have 30 fitters then it is going to be tough to get your stuff" (Fitter East) did not hold true, at least in relation to spare parts.

Regarding tools, maintenance staff outlined during the focus group interview in 2019 that visibility was reduced when comparing the old and the new maintenance resource network. Respondents explained, that when tools were kept decentralized in several locations, it was easy to spot what tools were available and who was using them in case they were not in the warehouse; centralization reduced and clouded such visibility. Furthermore, the fact that the central warehouse is further away (see also logistics of manpower), with increased geographical spread of the work domain (see also localization/composition of manpower), resulted in fitters having less opportunities to return tools to the central warehouse after conducting maintenance. In addition, to get spare parts and tools for corrective maintenance to the point of disruption, distances may be larger and, hence, driving costs higher and velocity somewhat reduced.

Manpower

We find that the centralization of the warehouse and organizational structure led to a reduction in the quantity of manpower and, hence, costs. As was anticipated there are "less [fitters] with the new structure" (Head of Maintenance Distribution) with a decrease from 32 to 30. Further savings were achieved by hiring 10 new fitters (due to retirement of staff) of which only two had prior maintenance experience. The focus group interview in 2019 highlighted that starters are able to conduct smaller, more routine maintenance work on their own, but require approximately two years until they have acquired all competences. As such, there is less flexibility in the workforce. To ensure that new fitters gain more experience and develop their competencies to become all-rounders as required by the geographical spread and network properties, schedulers assign them as much as possible to conduct work together with experienced fitters. In summary, currently the competence level (and inherent resilience) is a bit lower than it was prior to the change, however, this is not necessarily linked only to the re-organization, but can also be attributed to general staff turnover.

With regards to competency development, the analysis of the data suggests that there are better opportunities to build tacit knowledge between planners, fitters and warehousing staff in the new set-up linked to the centralized organizational structure in one location. In the old maintenance supply network, planning and allocation of staff were less standardized and the two locations had "their own manner of work" (Fitter North). Hence, it was anticipated that when centralizing "knowledge can be exchanged with your colleagues" (Fitter East). As such, "the group will be more robust" (Head of Water Supply) as the new structure allows the creation of a common knowledge base. "That is why the fitters are for centralization" (Fitter North). The interview with the fitters in 2019 confirmed this as there is now "not them and us but one group". The centralization of manpower has also allowed for scheduling to become more flexible as there is a bigger pool of fitters to draw on and "planners can plan more efficient when sitting together" (Head of Water Supply) ensuring better usage of capacity (costs) and allocation of manpower to preventive and corrective maintenance activities (resilience).

At the same time, however, although the centralization created a common planning domain and standardized ways of working that helped to increase some elements of resilience, there are now fewer chances to collaborate and "exchange information, knowledge and expertise" (Head of Maintenance Distribution) outside of planned bi-weekly meetings at the centralized warehouse. "The way it is set up is bad for the communication of fitters. We rarely see each other and do not know where maintenance work is/has taken place" (Additional remark 2019). Yet, as outlined above, CI characteristics require close communication and face-to-face contact to ensure the build-up of tacit knowledge which influences velocity. It appears, that decreased direct contact has been partly substituted with increased mobile communication, yet cannot make up for some loss of motivation. Furthermore, belonging to a larger group and the fact that maintenance staff can be scheduled in the overall network rather than "their own" part resulted in a decline "the feeling of responsibility and needs to increase again" (Fitter, Focus Group Interview 2019). This is important as the high intrinsic motivation of fitters and a feeling of responsibility ensures that they do a high-quality job and provide good service in line with the company philosophy. Taken together, some aspects of manpower centralization seem to increase resilience and others to decrease it.

Regarding the logistics of manpower, we find that in the new maintenance supply network, staff start their work from home rather than first driving to one of the satellite warehouses. As such, less fuel is required (reduction in costs) while redundancy is increased due to increased work capacity (increased resilience). At the same time, fitters have to drive further to pick up stock from the central warehouse (rather than decentralized ones) for preventive maintenance and for fixing large calamities. "This causes more transport movements with greater distance, which results in more fuel consumption, and that times 30! You came by the warehouse more often in the old design because it was on-route. Now, you have to drive past it separately or even schedule it." (Additional remark, 2019). Hence, the centralization of resources led to an overall increase in the cost of logistics. At the same time, however, the average response time between a disruption being registered by the call center and fitters reaching the leakage spot remained about one hour (Internal Document) and as such the increased logistics did not lead to a decrease in velocity.

Discussion

Centralization is typically used to gain efficiencies by consolidating resources in fewer central locations. Indeed, our findings show that with the centralized warehouse, planning and organizational structure, the quantities of all resources (tools, spare parts and manpower) were reduced. Considering the legal requirements of the case, keeping less spare parts was not done at the expense of the availability of spare parts and, hence, did not influence resilience. At the same time, however, given the geographical spread of the CI network, while there were efficiency gains due to reduced quantities of resources, the logistics activity of all resources increased. As such, cost advantages of centralization do not seem to be straightforward in geographically spread networks and are dependent on the difference between savings in the quantity of resources and the increased logistics activity:

P1a. In CI networks, efficiency gains through centralizing resources (location decision) can lead to efficiency losses through increased logistics activity of resources.

In terms of resilience, while there are reduced redundancies, there is also increased visibility of spare parts (better overview in one location) and flexibility of manpower (in terms of scheduling in one planning domain across the whole network) along with decreased visibility of tools (due to increased logistics activity with less opportunities for return). Therefore, resilience in CI networks is not a straightforward trade-off between efficiency versus redundancy as some literature suggests (Christopher and Peck, 2004). Particularly considering legislative influences that can pre-determine resilience (e.g. 24-h response) the question of efficiency versus redundancy seems to be less relevant: reduction of redundancy will always be second to resilience:

P1b. In CI networks, efficiency gains through centralizing resources (location decision) can lead to resilience losses through increased logistics activity of resources.

When dealing with CIs, there are aspects complementary to the structural/technical network elements which embrace social dimensions (Cantelmi *et al.*, 2021). People (human resources) not only manage, plan, supervise and execute all maintenance practice (Cholasuke and Antony, 2006; Simões *et al.*, 2011), but are also the greatest source of information (tacit knowledge) as they are most familiar with the daily operation of the equipment and the technical specifications and long run performance of that equipment (McKone *et al.*, 1999). As such, the centralization of the warehouse, planning and organizational structure not only affected the formal network, but also informal aspects in terms of motivation and collaboration (tacit knowledge creation). On the one hand, the decision to co-locate manpower resources enabled increased standardized tacit knowledge creation across the overall maintenance team. On the other hand, by eliminating structural aspects in the maintenance supply network (i.e. the decentralized warehouses) the organization took away a facilitator of the informal network that was used to access, exchange and transmit tacit knowledge about specific CI network properties. Given the high interactive complexity in CI networks, it is difficult to have standardized documentation or detailed formal procedures. Maintenance staff are often required to act independently within a frame of reference set between the deductive logic of formal network design and tacit experience-based knowledge to ensure robustness and agility (Schulman and Roe, 2007). As such, well-informed decentralized decision-making and local knowledge are important but less supported in centralized planning structures. We therefore propose:

P2. To build resilience in CI maintenance supply networks, the centralization of resources needs to be supported by decentralized organizational structures (location of manpower/planning) that facilitate tacit knowledge creation and exchange.

Beyond tacit knowledge creation, it is also important to fully understand motivation and morale of human resources before any organizational redesign is attempted (Kelly, 2006; Simões *et al.*, 2011). Our findings show that motivation has an important influence on the work of maintenance staff. In addition, our results indicate that motivation was affected by the re-design of the structural maintenance resource network. While we cannot ascertain how the change affected resilience and/or costs exactly we know that motivation affects productivity (Edwards, 1987), productivity affects efficiency (Duffuaa *et al.*, 2001) and efficiency links to both resilience and costs. Hence, it is important to understand what supports the motivation of maintenance staff in the structural maintenance resource network configuration. In this specific case, the motivation of staff is linked to contributing to the "greater good", but also to having opportunities to have social encounters such as meeting other staff and exchanging knowledge on a daily basis, which was less possible in the new network design. Our findings indicate that in CI supply networks resilience requires leveraging knowledge and creating tacit knowledge through informal relationships similar to the findings by Poberschnigg *et al.* (2020) on the role of informal groups in building supply chain resilience.

Theoretical implications

The above discussion provides insights into how supply chain resilience knowledge can be contextualized to a specific setting as called for by e.g. Scholten *et al.* (2020). Furthermore, our findings on tacit knowledge and motivation contribute to and complement resilience literature, which is mainly focused on formal, physical structures linked to the decisions regarding factors such as the quantity of (redundant) resources (Tukamuhabwa *et al.*, 2015). Surprisingly, decisions linked to more informal structures and processes are less prevalent. While training, skills and knowledge management are proposed by many researchers to contribute to supply chain resilience (Ali *et al.*, 2022; Fearne *et al.*, 2021; Sawyerr and Harrison, 2019), considerations of the underlying structures that facilitate the creation and renewal of them are rare (Poberschnigg *et al.*, 2020 for an exception). Our findings show that in a CI context, it is particularly important to pay attention to organizational structures that facilitate the creation and transfer of tacit knowledge.

Furthermore, while learning has always been a key facilitator of supply chain resilience (Scholten *et al.*, 2019), the recently started debate of supply chain resilience as engineering or social-ecological resilience (Wieland and Durach, 2021) seems to associate change and, hence, learning, with social-ecological resilience only. Yet, as this case of CI shows, in a supply network that is meant to enable engineering resilience (i.e. bouncing back after a disruption in the most efficient way), learning and human agency play an important role. Accordingly, the idea of change and adaption is essential in engineering resilience (Yu *et al.*, 2020) and also engineered networks are complex adaptive systems (Haghnevis and Asking, 2012). This raises the question whether we should distinguish between different types of resilience in the supply chain management domain in the way Wieland and Durach (2021) suggest. As Park *et al.* (2013, p. 357) argue: "an important difference between ecological and engineering systems in this respect is intentionality […] engineering systems, as the product of design and management, exhibit human intention (direct control) to a much greater extent". This would suggest that supply chain resilience relates for a large part to engineering resilience while naturally linking to "other social-ecological systems that operate on other levels (e.g. the political economy or planet earth)" (Wieland and Durach, p. 319).

Finally, our study also provides a new view on the relationship between NAT and HRT (Shrivastava *et al.*, 2009). As discussed in the theoretical background, according to NAT, disruptions are inevitable due to tight coupling and interactive complexity linked to the formal structures of a network (Leveson *et al.*, 2009). At the same time, our case shows that the resilience of CI maintenance supply networks not only depends on the formal NAT structures of the maintenance supply network (e.g. level of redundancy), but also on informal structures (e.g. the human actions and knowledge) as also outlined above. The latter supports the notion of HRT that organizations can become highly reliable and avoid/reduce network accidents through appropriate processes and management practices that help to deal with interactive complexity (Sawyerr and Harrison, 2019). In an earlier attempt to reconcile NAT and HRT, Shrivastava *et al.* (2009) concluded that HRT offers insights before a disruption and NAT identifies the key elements of the maintenance supply network at the point in time in which an accident occurs. Interestingly, and in contrast with HRT's predominant focus on accident avoidance, we find that in this specific CI network, HRT principles are particularly important after an accident has occurred. More so, disruptions avoidance in CI networks can be difficult due to limited visibility resulting from the geographical spread, location and properties of the maintenance supply network. Hence, decentralization and giving lower-level operators the autonomy to respond to emerging problems is of essence.

Implications for practice and society

In the development of maintenance resource networks so far (both in practice and in the academic literature) there has been a tendency to focus on structural design aspects. Our findings provide cause and effect outcomes for cost and resilience linked to structural resource configurations. At the same time, previous research found that solutions focused on system design, usually applying optimization techniques, have not necessarily been accepted in practice (Garg and Deshmukh, 2006). We find that considerations of the informal structures that derive from formal structures ensuring that operational staff remain motivated and obtain the required tacit knowledge is critical for organization in CI. This is due to factors such as the need to take more decisions under increased time pressure in a decentralized environment. As human behavior is difficult to include into optimization techniques, it might provide the explanation as to why these have not been accepted in practice to date. Accordingly, we recommend that CI management to considers how to facilitate informal structures in the best possible way when configuring a maintenance resource network. This could include consulting with maintenance staff to find out what social structures are important for them. Doing so will help with the resilience of the CI supply network via the facilitation of tacit knowledge exchange and increased motivation which in turn indirectly contributes to society by reducing time to recover from disruptions in the most cost-efficient way.

Conclusions

In CI networks, maintenance facilitates resilience and as such reduces social and economic costs that might occur due to disruptions (Cantelmi *et al.*, 2021). The findings of this study underline that it is particularly important for CI supply networks to approach maintenance management strategically and systematically (Simões *et al.*, 2011) as it is a key determinant of the resilience of the network (Blokus and Dziula, 2021). Contextualizing resilience to the CI setting, we were able to generate new insights on maintenance resource configurations for both structural and social elements. Furthermore, we were able to elaborate on NAT and HRT theory.

There are some limitations to consider, some of which present opportunities for future research. In exploring the supply network for this specific water supply company in The Netherlands, we did not consider external resources and work design factors that might interact with internal resources e.g. service contractors. Depending on the usage of external resources, these might influence resource decisions and alter some of the outcome dynamics. Hence, for future research, we suggest to further extend the scope of the supply network studied and also incorporate external resources that might interact with the CI maintenance supply network. In addition, while we consider disruptions, we recognize that the findings may not be relevant to dealing with catastrophic events that might impact the overall system in several places at once such as e.g. caused by a terrorist attack. Furthermore, we did not consider dependencies between different CI networks that might necessitate further design and management considerations. Accordingly, we recommend that future research extends our study to low probability and high impact disruptions and interactions with other CI providers.

References

Ali, I., Golgeci, I. and Arslan, A. (2022), "Achieving resilience through knowledge management practices and risk management culture in agri-food supply chains", *Supply Chain Management: An International Journal*, doi: 10.1108/SCM-02-2021-0059.

Ali, A., Mahfouz, A. and Arisha, A. (2017), "Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review", *Supply Chain Management: An International Journal*, Vol. 22 No. 1, pp. 16-39.

Almklov, P.G. and Antonsen, S. (2014), "Making work invisible: new public management and operational work in critical infrastructure sectors", *Public Administration*, Vol. 92 No. 2, pp. 477-492.

Balzer, G. and Schorn, C. (2015), *Asset Management for Infrastructure Systems: Energy and Water*, Springer, eBook, Vieweg Berlin, Heidelberg.

Blokus, A. and Dziula, P. (2021), "Relations of imperfect repairs to critical infrastructure maintenance costs", *Sustainability*, Vol. 13 No. 9, pp. 1-19.

Boin, A. and McConnell, A. (2007a), "Editorial: unravelling the puzzles of critical infrastructures", *Journal of Contingencies and Crisis Management*, Vol. 15 No. 1, pp. 1-3.

Boin, A. and McConnell, A. (2007b), "Preparing for critical infrastructure breakdowns", *Journal of Contingencies and Crisis Management*, Vol. 15 No. 1, pp. 50-59.

Cantelmi, R., Di Gravio, G. and Patriarca, R. (2021), "Reviewing qualitative research approaches in the context of critical infrastructure resilience", *Environment Systems and Decisions*, Vol. 41 No. 3, pp. 341-376.

Cedergren, A., Johansson, J. and Hassel, H. (2018), "Challenges to critical infrastructure resilience in an institutionally fragmented setting", *Safety Science*, Vol. 110, pp. 51-58.

Cholasuke, C. and Antony, J. (2006), "The status of maintenance management in UK manufacturing organisations: results from a pilot survey", *Journal of Quality in Maintenance Engineering*, Vol. 10 No. 1, pp. 5-15.

Chowdhury, M.M.H. and Quaddas, M. (2016), "Supply chain readiness, response and recovery for resilience", *Supply Chain Management: An International Journal*, Vol. 21 No. 6, pp. 709-731.

Christopher, M. and Peck, H. (2004), "Building the resilient supply chain", *The International Journal of Logistics Management*, Vol. 15 No. 2, pp. 1-13.

Dittfeld, H., van Donk, D.P. and van Huet, S. (2022), "The effect of production system characteristics on resilience capabilities: a multiple case study", *International Journal of Operations & Production Management*, Vol. 42 No. 13, pp. 103-127.

Dominguez, D., Worch, H., Markard, J., Truffer, B. and Gujer, W. (2009), "Closing the capability gap: strategic planning for the infrastructure sector", *California Management Review*, Vol. 51 No. 2, pp. 29-50.

Dube, N., Li, Q., Selviaridis, K. and Jahre, M. (2022), "One crisis, different paths to supply resilience: the case of ventilator procurement for the COVID-19 pandemic", *Journal of Purchasing and Supply Management*, Vol. 28 No. 5, doi: 10.1016/j.pursup.2022.100773.

Duffuaa, S.O., Ben-Daya, M., Al-Sultan, K.S. and Andijani, A.A. (2001), "A generic conceptual simulation model for maintenance systems", *Journal of Quality in Maintenance Engineering*, Vol. 7 No. 3, pp. 207-219.

Edwards, J.D. (1987), "Improved utilization of maintenance manpower", *Maintenance Management International*, Vol. 6, pp. 285-293.

Fearne, A., Wagner, B., McDougall, N. and Loseby, D. (2021), "The power of purpose – lessons in agility from the ventilator challenge", *Supply Chain Management: An International Journal*, Vol. 26 No. 6, pp. 753-766.

Garg, A. and Deshmukh, S.G. (2006), "Maintenance management: literature review and directions", *Journal of Quality in Maintenance Engineering*, Vol. 12 No. 3, pp. 205-238.

Haghnevis, M. and Asking, R.G. (2012), "A Modeling framework for engineered complex adaptative systems", *IEEE Systems Journal*, Vol. 6 No. 3, pp. 520-530.

Hastings, N.A.J. (2015), *Physical Asset Management*, Springer International Publishing, eBook, Switzerland.

Hemme, K. (2015), "Critical Infrastructure protection: maintenance is national security critical infrastructure protection: Maintenance is national security", *Journal of Strategic Security*, Vol. 8 No. 3, pp. 25-39.

Hillmann, J. (2021), "Disciplines of organizational resilience: contributions, critiques, and future research avenues", *Review of Managerial Science*, Vol. 15 No. 4, pp. 879-936.

Hopp, W.J. (2008), "Supply chain ccience", Waveland Press, Inc., Long Grove, IL.

Hovden, J., Albrechtsen, E. and Herrera, I.A. (2010), “Is there a need for new theories, models and approaches to occupational accident prevention?”, *Safety Science*, Vol. 48 No. 8, pp. 950-956.

Jüttner, U. and Maklan, S. (2011), “Supply chain resilience in the global financial crisis: an empirical study”, *Supply Chain Management: An International Journal*, Vol. 16 No. 4, pp. 246-259.

Kelly, A. (2006), *Managing Maintenance Resources*, Elsevier Butterworth-Heinemann.

La Porte, T.R. (1996), “High Reliability organizations: unlikely, demanding and at risk”, *Journal of Contingencies and Crisis Management*, Vol. 4 No. 2, pp. 60-71.

Leveson, N., Dulac, N., Marais, K. and Carroll, J. (2009), “Moving beyond normal accidents and high reliability organizations: a systems approach to safety in complex systems”, *Organization Studies*, Vol. 30 Nos 2/3, pp. 227-249.

Linnenluecke, M.K. (2017), “Resilience in business and management research: a review of influential publications and a research agenda”, *International Journal of Management Reviews*, Vol. 19 No. 1, pp. 4-30.

McKone, K.E., Schroeder, R.G. and Cua, K.O. (1999), “Total productive maintenance: a contextual view”, *Journal of Operations Management*, Vol. 17 No. 2, pp. 123-144.

Marais, K.B. and Saleh, J.H. (2009), “Beyond its cost, the value of maintenance: an analytical framework for capturing its net present value”, *Reliability Engineering and System Safety*, Vol. 94, pp. 644-657.

Miles, M.B. and Huberman, M.A. (1994), *Qualitative Data Analysis*, Saga Publications, London.

Ouyang, M. (2014), “Review on modeling and simulation of interdependent critical infrastructure systems”, *Reliability Engineering and System Safety*, Vol. 121, pp. 43-60.

Park, J., Seager, T.P., Rao, P.S.C., Convertino, M. and Linkov, I. (2013), “Integrating risk and resilience approaches to catastrophe management in engineering systems”, *Risk Analysis*, Vol. 33 No. 3, pp. 356-367.

Perrow, C. (1984), *Normal Accidents: Living with High Risk Technologies*, Princeton University Press, Princeton, NJ.

Pettit, T.J., Croxton, K.L. and Fiksel, J. (2013), “Ensuring supply chain resilience: development and implementation of an assessment tool”, *Journal of Business Logistics*, Vol. 34 No. 1, pp. 46-76.

Pettit, T.J., Croxton, K.L. and Fiksel, J. (2019), “The Evolution of resilience in supply chain management: a retrospective on ensuring supply chain resilience”, *Journal of Business Logistics*, Vol. 40 No. 1, pp. 56-65.

Pintelon, L.M. and Gelders, L.F. (1992), “Maintenance management decision making”, *European Journal of Operational Research*, Vol. 58 No. 3, pp. 1-317.

Poberschnigg, T. D S., Pimenta, M.L. and Hilletofth, P. (2020), “How can cross-functional integration support the development of resilience capabilities? The case of collaboration in the automotive industry”, *Supply Chain Management: An International Journal*, Vol. 25 No. 6, pp. 789-801.

Ponomarov, S.Y. and Holcomb, M.C. (2009), “Understanding the concept of supply chain resilience”, *The International Journal of Logistics Management*, Vol. 20 No. 1, pp. 124-143.

Reuter, C., Foerstl, K., Hartmann, E. and Blome, C. (2010), “Sustainable global supplier management: the role of dynamic capabilities in achieving competitive advantage”, *Journal of Supply Chain Management*, Vol. 46 No. 2, pp. 45-63.

Saleh, J.H. and Marais, K. (2006), “Reliability: how much is it worth? Beyond its estimation or prediction, the (net) present value of reliability”, *Reliability Engineering & System Safety*, Vol. 91 No. 6, pp. 665-673.

Sawyerr, E. and Harrison, C. (2019), “Developing resilient supply chains: lessons from high-reliability organisations”, *Supply Chain Management: An International Journal*, Vol. 25 No. 1, pp. 77-100.

Scholten, K. and Schilder, S. (2015), “The role of collaboration in supply chain resilience”, *Supply Chain Management: An International Journal*, Vol. 20 No. 4, pp. 471-484.

Scholten, K., Sharkey Scott, P. and Fynes, B. (2019), “Building routines for non-routine events: supply chain resilience learning mechanisms and their antecedents”, *Supply Chain Management: An International Journal*, Vol. 24 No. 3, pp. 430-442.

Scholten, K., Stevenson, M. and van Donk, D.P. (2020), “Dealing with the unpredictable: supply chain resilience”, *International Journal of Operations & Production Management*, Vol. 40 No. 1, pp. 1-10.

Schulman, P.R. and Roe, E. (2007), “Designing Infrastructures: dilemmas of design and the reliability of critical infrastructures”, *Journal of Contingencies and Crisis Management*, Vol. 15 No. 1, pp. 42-49.

Schulman, P., Roe, E., van Eeten, M. and de Bruijne, M. (2004), “High reliability and the management of critical infrastructures”, *Journal of Contingencies and Crisis Management*, Vol. 12 No. 1, pp. 14-28.

Shrivastava, S., Sonpar, K. and Pazzaglia, F. (2009), “Normal Accident theory versus high reliability theory: a resolution and call for an open systems view of accidents”, *Human Relations*, Vol. 62 No. 9, pp. 1357-1390.

Simões, J.M., Gomes, C.F. and Yasin, M.M. (2011), “A literature review of maintenance performance measurement: a conceptual framework and directions for future research”, *Journal of Quality in Maintenance Engineering*, Vol. 17 No. 2, pp. 116-137.

Skilton, P.F. and Robinson, J.L. (2009), “Traceability and normal accident theory: how does supply network complexity influence the traceability of adverse events”, *Journal of Supply Chain Management*, Vol. 45 No. 3, pp. 40-53.

Tsang, A.C. (2002), “Strategic dimensions of maintenance management”, *Journal of Quality in Maintenance Engineering*, Vol. 8 No. 1, pp. 7-39.

Tukamuhabwa, B.R., Stevenson, M., Busby, J. and Zorzini, M. (2015), “Supply chain resilience: definition, review and theoretical foundations for further study”, *International Journal of Production Research*, Vol. 53 No. 18, pp. 5592-5623.

Van den Adel, M.J., de Vries, T.A. and Van Donk, D.P. (2022), “Resilience in interorganizational networks: dealing with day-to-day disruptions in critical infrastructures”, *Supply Chain Management: An International Journal*, Vol. 27 No. 7, pp. 64-78.

Welch, C., Piekkari, R., Plakoyiannaki, E. and Paavilainen-Mäntymäki, E. (2011), "Theorising from case studies: towards a pluralist future for international business research", *Journal of International Business Studies*, Vol. 42 No. 5, pp. 740-762.

Wieland, A. and Durach, C.F. (2021), "Two perspectives on supply chain resilience", *Journal of Business Logistics*, Vol. 42 No. 3, pp. 315-322.

Wiengarten, F., Fan, D., Lo, C.K.Y. and Pagell, M. (2017), "The differing impacts of operational and financial slack on occupational safety in varying market conditions", *Journal of Operations Management*, Vol. 52 No. 1, pp. 30-45.

Wiengarten, F. and Longoni, A. (2018), "How does uncertainty affect workplace accidents? Exploring the role of information sharing in manufacturing networks", *International Journal of Operations & Production Management*, Vol. 38 No. 1, pp. 295-310.

Yin, R.K. (2009), *Case Study Research: Design and Methods*, Sage Publications, London.

Yu, D.J., Schoon, M.L., Hawes, J.K., Lee, S., Park, J., Rao, P.S.C., Siebeneck, L.K. and Ukkusuri, S.V. (2020), "Toward General principles for resilience engineering", *Risk Analysis*, Vol. 40 No. 8, pp. 1509-1537.

Corresponding author

Kirstin Scholten can be contacted at: k.scholten@rug.nl